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COMPARISON OF ELECTRICAL STIMULATION AND
MAXIMUM VOLUNTARY CONTRACTION
ISOMETRIC TORQUES

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled:

Comparison of Electrical Stimulation
and Maximum Voluntary Contraction Isometric Torques

submitted by: David M. Lindsay

in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

Electrical stimulation, for the restoration of normal bodily function, has long played a beneficial role in therapy. It has not been until recently, however, that the use of electrotherapy for the hyperdevelopment of normal muscle has been investigated.

Interest in the use of electrical muscle stimulation (E.M.S.) for strength facilitation within normal muscle increased with reports of Soviet experiments claiming strength gains of between 30 and 40 percent in already highly trained athletes following four (4) to five (5) weeks of E.M.S. training. The advantageous use of E.M.S. for strength gain was based on the theory that more motor units were recruited with this type of maximum contraction as compared to maximum voluntary contraction (M.V.C.) and resulted in a stronger contractile force.

Based on the unconfirmed Soviet findings and evidence suggesting that not all available muscle fibers were recruited during M.V.C., it was the purpose of the present study to investigate how M.V.C. torque compared with maximal E.M.S. torque and combined torque - M.V.C. with superimposed E.M.S., using the right quadriceps muscle group of 30 normal, healthy male subjects, performing isometric knee extension exercise. The present experiment also compared three (3) separately manufactured E.M.S. units, emitting three (3) distinct current formats, to examine which current format generated the greatest torque magnitude. A special knee extension dynamometer, using strain gauges to measure resisted isometric torque was used in the study.

The results of the study showed that the mean torque generated in the combined maximal contraction (C.M.C.) condition equalled but did not surpass torque generated in the M.V.C. condition for all groups tested. Additionally, of the three current formats used, only that emitted by the TECA E.M.S. unit was associated with quadriceps torque equal to, but not greater than, M.V.C. or C.V.C. mean torque. Subjects stimulated by the Medelco or Siemens current formats generated significantly lower mean torque ($p < 0.05$) in the E.M.S. only contraction condition than in the respective M.V.C. or C.M.C. contraction conditions. Comparisons of mean torque generated within the E.M.S. only contraction condition revealed that subjects stimulated by the TECA current format generated significantly higher mean torque ($p < 0.05$) than subjects stimulated by the Medelco or Siemens current formats. Subjects stimulated by the Medelco current format generated significantly higher mean torque ($p < 0.05$) than subjects stimulated by the Siemens current format.

The conclusions drawn from this study were that: 1) E.M.S. did not recruit more motor units, resulting in a stronger force of contraction than M.V.C., in fact, depending on the E.M.S. unit used, fewer motor units were often recruited, and 2) the mean E.M.S. only torques associated with the three (3) stimulators were not equal due to the distinct current qualities and different maximum administrable intensities available on each unit.

Overall, it would appear that E.M.S. is potentially no more effective in the hyperdevelopment of normal muscle than the more traditional voluntary strength improvement techniques.

ACKNOWLEDGEMENTS

Completion of this thesis could not have been accomplished without the assistance of many people. These people gave freely and unselfishly their time and advice over an extended period of time and for that I am most grateful.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

In an effort to achieve the ultimate in sports performances, man has continually strived to discover new methods for enhancing athletic ability. Improvements in performance have generally been attributable to improved training methods or to the use of ergogenic aids. Electrical muscle stimulation (E.M.S.) for the purpose of increasing strength related parameters could be classified within either of the above categories.

Electrical muscle stimulation cannot accurately be described as a phenomenon of modern day technology but rather has been a refinement of procedures introduced over two hundred years ago.[36] In 1744, Kratzenstein (as reported in Licht[36]) used electricity to restore complete function in a woman suffering from paralysis of the little finger. In tracing the use of electrical stimulation over the past few centuries,[36] the predominance of investigation has centered around the therapeutic benefits of low dosage electricity in the restoration of normal bodily function after injury or disease. Some of the conditions reportedly treated by electrical stimulation include: nerve degeneration, muscle degeneration (re-education), arthritis, mental disorders, paralysis, dystrophies, circulatory disorders, neuralgia, systemic disease, poliomyelitis, muscle spasm, phlebitis, and neck and low back pain.[36] Stillwell[50] reported that the retardation of the negative effects of muscle degeneration, represented the most documented

use of electrical stimulation. In recent years more and more emphasis has focused on the use of electrical stimulation for the limitation and rehabilitation of atrophied, but otherwise normal muscle.[18,22,52]

As the body of knowledge regarding the rehabilitation benefits of E.M.S. expanded, researchers began investigating the possible application of E.M.S. as a strength training modality. Interest in the use of E.M.S. for the hyperdevelopment of normal muscle was boosted in 1975 when results of Soviet experiments, performed by Kots and Chuilon[34] were released. The Soviet study described strength gains in already highly trained athletes of between 30 and 40 percent following four (4) to five (5) weeks of E.M.S. training.

The question of whether E.M.S. can enhance muscular strength to a greater degree than the traditional voluntary methods of training (for example: isotonic free weight resisted exercises, maximal isometric contraction exercises) has not adequately been answered. The inconsistencies documented in past literature extend not only to the long term benefits of this type of training, but also to the immediate biochemical and physiological effects which occur when a muscle is made to contract by artificial electrical means. It has been suggested that the advantageous use of E.M.S. for strength gain is due to greater motor unit recruitment when the contraction is induced by external electrical stimuli than when the muscle is made to maximally contract voluntarily.[35] Pinelli[42] explained,

> "... Voluntary recruitment of motor units is asynchronous and even at full effort the resulting E.M.G. shows only a partial irregular algebrical summation of motor unit action potentials."

Ikai et al.[30] (as reported by Simonson[48]) after performing a series of experiments comparing E.M.S. and maximal voluntary contraction (M.V.C.), claimed that "only 70 percent of all fibers were activated with maximal voluntary effort." It is not known how the authors arrived at this percentage magnitude. Fisher and Jensen[20] claimed that depending on the state of muscular conditioning, between 60 and 90 percent of available motor units were recruited with maximum voluntary contraction. Pinelli,[42] using surface electrode E.M.G. analysis, stipulated that during M.V.C., there was a rotation of motor units incorporated, so that at any one time some motor units were held in reserve. Merton[37] commented that such a functional reserve was found in many body tissues aside from skeletal muscle, for example, the heart, liver, kidneys, and possibly even the cerebral cortex. It was the existence of this functional reserve as Hansen and Lindhard[27] suggested, that allowed lunatics or patients suffering from convulsions or tetanus to develop muscular force quite out of proportion to what the same individuals were able to yield under normal conditions.

The recruitment characteristics of skeletal muscle fibers are documented as due to histochemical and electromyographical properties.[10] Human skeletal muscle is essentially comprised of two (2) different types of muscle fibers; type I, slow twitch; and type II, fast twitch. A third fiber type, type II slow twitch, is

reported in the literature and is characteristically similar to the type II fast twitch with the exception that its endurance component is longer.[14] For simplicity purposes only the two (2) distinct fiber types (type I and type II) are discussed here.

Histochemically, type I muscle fibers are characterized by low myosin ATPase activity and high oxidative activity. Type II muscle fibers are histochemically characterized by high glycolytic and myosin ATPase activity, but low oxidative capacity. Physiologically, type I fibers demonstrate slower contraction time and hence excitation frequency, and greater fatigue resistence than type II muscle fibers. Anatomically, type I fibers are smaller in diameter and reddish in colour while type II fibers maintain a larger diameter and are white in appearance.[10]

In order to graduate the amount of force developed and minimize fatigue in muscle undergoing voluntary contraction, the relative recruitment proportion of each of the fiber types is altered.[17] Overall, the tension generated is proportional to the contracting muscle's electrical activity, indicating that new motor units are being recruited right up to maximum voluntary contraction.[3] At low tension levels of moderatively sustained contractions it is the smaller low excitation frequency muscle fibers (type I) which are preferentially recruited. As the force generated by the muscle approaches maximum, or, if the nature of the contraction necessitates speed, type II fiber recruitment becomes more predominant.[17,23,26] When type I muscle fibers are preferentially recruited, the discharge activity from such fibers remains constant for the duration that the contraction is held.

The frequency of discharge rarely exceeds 30 per second.[23] The constant nature of type I discharge activity indicates that the endurance capabilities of these muscle fibers are adequate such that few auxillary fibers are needed. When type II muscle fibers are brought into play by increasing the rate of force production or by performing a M.V.C., the activity pattern of these fibers is characterized by bursts of activity lasting only a few milliseconds.[23] The discharge frequency during such bursts can exceed 100 per second.[23] The intermittent nature of type II muscle fiber recruitment indicates a greater fatigue of these fibers as compared to their slow twitch counterparts. Since the duration time that a single fast twitch muscle fiber can remain active is so short, it would appear that many of the type II fibers are held in reserve enabling a rotation into service as the fibers fatigue.[23]

One of the prime determinants of the amount of force a muscle is able to generate is the number of muscle fibers activated.[17] Increased force of contraction, occurring as a result of greater muscle fiber recruitment is one of the basic underlying principles of strength gains from strength training. Aside from actual muscle fiber hypertrophy, strength training is thought to enable an easier tapping into the motor unit reserve supply thus facilitating any strength related performance.[1] Komi et al.,[33] in work with three (3) pairs of monozygous twins (one twin acted as the control while the other underwent the experimental treatment) showed that after 12 weeks of maximum isometric knee extension training, there was a significant increase ($p < 0.05$) in the maximum integrated electromyographic activity of the

rectus femoris muscle which occurred concomitantly with knee extension strength increase. The author postulated that the increased maximal intergrated E.M.G. activity was due to a training effect per se causing a reduction of inhibitory inputs to the muscle.

If E.M.S. is able to develop greater force of contraction over M.V.C., it must preferentially and simultaneously recruit type II muscle fibers. The ability of E.M.S. to preferentially recruit type II muscle fibers has been investigated by Poortman and Taylor [43] using a direct current of 1.0 milliseconds (ms) duration -- 50 cycles per second (cps). The authors stimulated eight (8) subjects twice per day for 10 days. The results of the study showed a significantly increased hypertrophy of fast twitch muscle fibers as compared to a control group (the significance level was not reported by the authors). Atrophy of slow twitch fibers was also present in the experimental group as compared to the control group.

To summarize what has been reported so far, it would appear that:

1. When a muscle contracts maximally it does not recruit all muscle fibers at its disposal. Type II muscle fibers are rotated into service rather than simultaneously activated.
2. Type II muscle fibers operate at an excitation frequency of between 30 and 100 per second.
3. Greater muscle fiber recruitment and increased force of contraction of the same muscle occur concomitantly.
4. Individual fiber types can be preferentially stimulated by electrical stimulation.

Based on the preceding it is suggested that E.M.S. operating at a frequency conducive to type II fiber recruitment can preferentially and simultaneously excite such fibers resulting in increased force of contraction.

It might be argued that simultaneous stimulation of all type II fibers available to a muscle may not result in increased force of contraction due to accelerated fatigue within such fibers. While it is true that type II muscle fibers fatigue very rapidly with M.V.C.,[10] a definite portion of this fatigue is due to centrally controlled recruitment inhibition.[23] Grimby and Hennerz [23] were able to show that when fast twitch muscle fibers from the short toe extensor muscles of humans could no longer respond to sustained maximal effort, electrical stimulation to the peroneal nerve could reactivate these fibers indicating a central control of fatigue.

I. STATEMENT OF THE PROBLEM

Soviet studies appear to have successfully used E.M.S. as a training modality for the hyperdevelopment of highly trained athletes' strength and endurance capabilities. Kots[35] claimed that E.M.S. enabled a more complete recruitment of the muscle fibers within a particular muscle thus permitting greater force of contraction. Contractile forces of between 10 and 30 percent higher for E.M.S. over M.V.C. were quoted by Kots.[35] Complete details of the Soviet experiment have not been made available to Western researchers, which limits to some degree the credibility of the Soviet claims.

Based on the questionable reliability of Kots and Chuilon[34] experimental results, and the evidence suggesting that indeed not all available muscle fibers are recruited during M.V.C, it was the purpose of the present study to investigate how M.V.C. torque compared with maximal E.M.S. torque and combined M.V.C. with superimposed E.M.S. torque using the right quadriceps muscle group of 30 normal healthy, male subjects, performing isometric knee extension exercise. Quadriceps torque was used as the representative index of contractile force due to the difficulty in measuring a muscle's force of contraction directly.

II. SUBPROBLEMS

Many medical instrument companies in recent years have recognized a demand for E.M.S. units capable of strengthening normally innervated muscle. As a result, a wide range of electrical stimulators have surfaced on the market, each claiming improvements over pre-existing units. It was a subproblem of this study to investigate which of the E.M.S. current formats tested generated the most E.M.S. torque. A list and description of the current formats under investigation is presented in Chapter Three.

A second subproblem of this study was concerned with the changes in maximal torque magnitudes recorded from subjects as subsequent maximal contractions were performed. A progressive rise or decrease in the mean maximal torque developed during each subject's four (4) repetitions of each contraction condition would have suggested that the subject gained knowledge in the initial contractions which influenced subsequent performance. For example, when E.M.S. only was used, a steady rise in

the mean torque magnitudes, as subjects progressed from trial 1 to trial 4, would have suggested that a consistent current tolerance level was not being maintained and subjects were still adjusting to the sensation.

III. HYPOTHESES

Three (3) null hypotheses were tested in this study:

1. The mean knee extension torques within each current format group and generated under each of the three (3) contraction conditions, M.V.C., E.M.S. only, and combined M.V.C. with E.M.S., were not significantly different from each other ($p < 0.05$).
2. No significant difference in mean torque existed ($p < 0.05$) between the different current format groups under the same contraction conditions.
3. The mean maximal torque, recorded in any of the four (4) trials, irrespective of the type of contraction or current format used, was equal to the mean torque obtained in any of the remaining respective trials.

IV. DELIMITATIONS

The delimitations of the study included:

1. The use of 30 normal, healthy, volunteer individuals, as the total sample population.
2. The use of only males in the sample.

3. The examination of maximal torques of only the right quadriceps muscle at one specific joint angle (60 degrees of knee flexion).
4. The limitation of E.M.S. intensity to subject tolerance.
5. The use of surface electrodes for E.M.S. application to stimulate the femoral nerve.

V. LIMITATIONS

The limitations of this study included:

1. The inability to ensure that a subject's contraction was indeed maximal.
2. The inability to ensure that all subject bias and order effects were randomly distributed in the assignment of subjects to treatment conditions.
3. The use of an external apparatus measuring maximal resistance torque, to represent contractile force within a muscle.
4. The use of the unmodified, non calibrated maximum output available for each E.M.S. unit tested.

VI. EXPLANATION OF TERMS

1. Contracile Force versus Measureable Torque

Confusion often exists when the terms force and torque are used. In this study, force refers to the tension developed within a muscle while undergoing contraction. For example, if each end of a muscle were attached to an immovable object and the muscle was then made

to contract, tension would develop within the muscle proportional to the amount of force placed on both the immovable objects.

Force developed within a muscle is not the same force measured by an external apparatus. As an example, Figure 1 illustrates the forces operating on the knee joint by the quadriceps mechanism during an isometric knee extension exercise. Contribution of other knee joint muscles are excluded for simplicity purposes. Since both the contractile force supplied by the quadriceps (E) and the resistance provided by the non elastic strap (R) are acting about a fixed point or fulcrum (F) both exert a turning effect on the lower limb. This turning effect is referred to as torque.[41] The amount of torque generated is equal to the magnitude of the forces involved multiplied by the perpendicular distance from the line of action that the force acts and the fulcrum (referred to as the moment arm and abbreviated MA). In the example illustrated in Figure 1, since no movement is elicited from the quadriceps contraction, the torque produced by the resistance strap must equal the magnitude of the torque generated by the quadriceps muscles:

$$E \times MA_E = R \times MA_R$$

If a resistance of 50 kilograms is recorded by the measuring device M, and the moment arms of the resistance and contracile forces are 0.20 and 0.05 meters respectively ($MA_R = 0.20$, $MA_E = 0.05$), then actual quadriceps force is equal to:

$$E \times 0.05 = 50 \times 0.02$$
$$E = 200 \text{ kilograms}$$

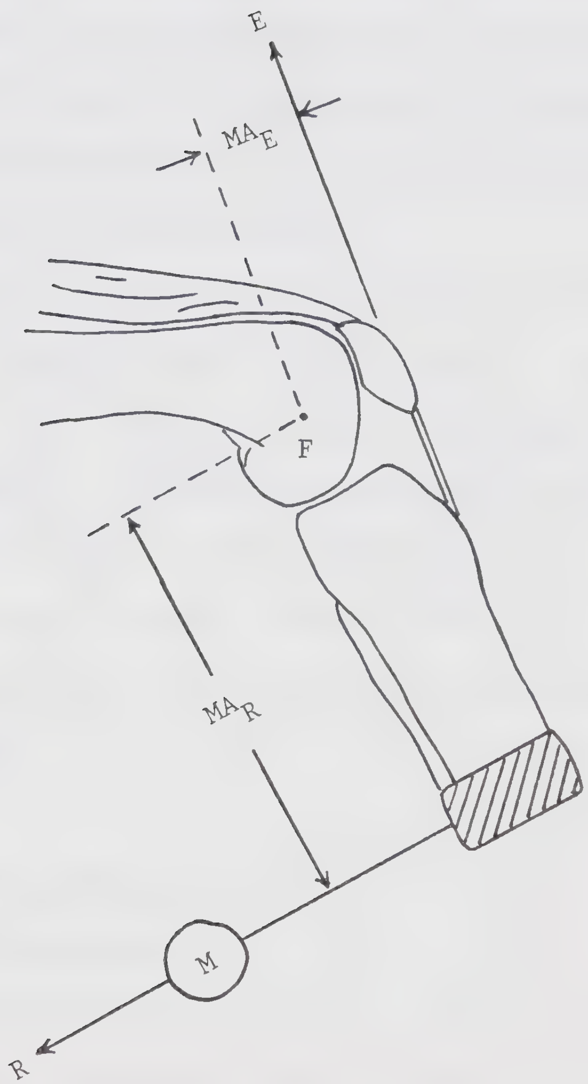

Figure 1 - Quadriceps and resistance forces acting on the knee joint during resisted knee extension (F - Fulcrum, E - quadriceps force, MA_E - moment arm of quadriceps force, R - resistance force, MA_R moment arm of resistance force and M - measurement apparatus).

It is evident therefore that although a force of 50 kilograms is recorded by the measuring instrument, the quadriceps muscles are pulling on the distal boney attachment with a force closer to 200 kilograms. The actual force developed by the quadriceps is further influenced by factors such as hip and knee joint angle, and the contribution of other antagonist, synergist or fixator muscles.[11]

The above example demonstrates that measures obtained from a mechanical recording apparatus are not the same as contractile forces produced by the muscle against its boney insertions, but rather are indicative of a number of interrelated factors which combine to give a representation of the actual tension generated. Due to the difficulty in measuring contractile tension directly, this study used isometric resistance torque as the representative means of comparing quadriceps forces of contraction.

2. Electrical Muscle Stimulation

A. Skeletal Muscle Contraction

Each of the E.M.S. units utilized in this study supplied faradic wave formats derived from either direct (Siemens) or alternating (TECA and Medelco) currents. To better understand how E.M.S. of this nature works, an understanding of the histological and anatomical neuromuscular components of skeletal muscle is presented.

Skeletal muscle is comprised of longitudinal muscle fibers characterized by a striated appearance, a connective tissue framework, and a

rich supply of blood vessels, lymphatic ducts and nerves.[11] Each muscle fiber, when examined microscopically, is made up of several thousand longitudinal myofibrils, with each myofibril comprised of thousands of actin and myosin filaments. The filaments are arranged so that each myosin filament sits between several actin fibers. It is the varying degrees of interdigitation or overlapping between the actin and the myosin filaments which give the myofibrils a striated appearance (Figure 2).[21]

The myosin filament is composed of approximately 200 myosin molecules, each having a molecular weight of approximately 450,000 moles per gram. Projecting at an angle away from the myosin filament, are single double stranded myosin molecules which possess at their outermost end globular protein "heads." Both the head to myosin molecule connection, and the myosin molecule to myosin filament connection are made by means of flexible "hinges" which enable some degree of microscopic movement. It is the globular protein head of the projecting myosin molecule which provides the means of attachment, or cross bridging, to the adjacent actin filaments.[24]

The actin filament is thinner, and more plentiful (there are six (6) surrounding a single myosin filament) than its myosin counterpart. The actin filament is composed of three (3) different protein constituents: actin, tropomyosin and troponin.[24] The actin protein component of the actin filament is actually a double stranded F-actin protein molecule wound into a helical configuration. Attached at intervals along the F-actin strand are single ADP molecules;

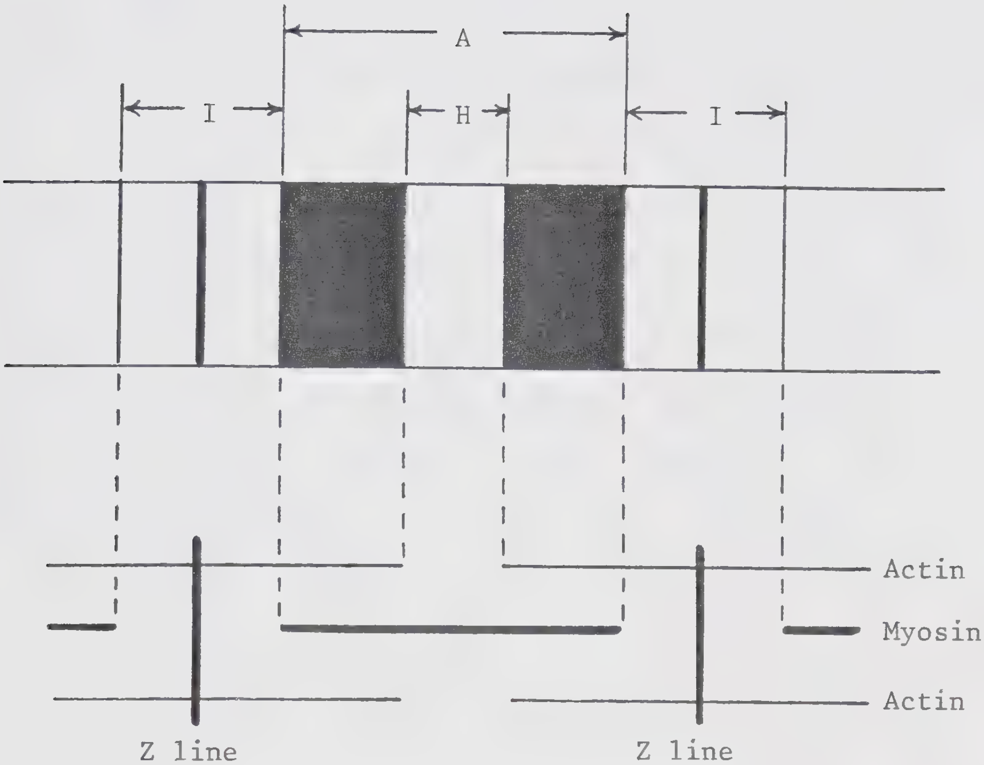

Figure 2 - Skeletal muscle striations corresponding to actin - myosin interaction. I band corresponds to actin filament only, A band reflects actin and myosin filaments while H band represents myosin filaments only (adapted from Guyton[24]).

thought to be the active sites for myosin cross bridge linking.[21]

Included in the actin filament, along with the F-actin strands, are two (2) additional protein strands of tropomyosin. The tropomyosin strands position themselves in the grooves created by the helicaling of the F-actin strands. Attached to the tropomyosin strands are the protein troponin molecules.[21] In the normal resting state of muscle, it is thought that the troponin-tropomyosin complex inhibits formation of cross bridges between the myosin molecules and the ADP activation sites on the F-actin strands. For contraction to occur, the theory most readily accepted is that calcium is released from the sarcoplasmic reticulum and preferentially attaches to the troponin molecules. This attachment pulls the tropomyosin strands deeper into the helix grooves thus exposing the ADP sites on the F-actin strands to the myosin molecule and permits cross bridges to form.[21,24]

Once cross bridges have formed between the actin and myosin filaments, some form of movement must occur to allow the muscle to powerfully shorten, and hence contract. No proven theory exists to explain such movement. The proposed mechanism of contraction is that as the myosin molecule "head" attaches to an activation site, the head flexes at its hinge connection. Once movement of the myosin head is complete, it breaks with the active site and links up with the next activation site along the F-actin strand (Figure 3). In this manner of cross bridge linking and unlinking, the actin filaments are able to glide over the top of the myosin filament, shortening the sacromere length and

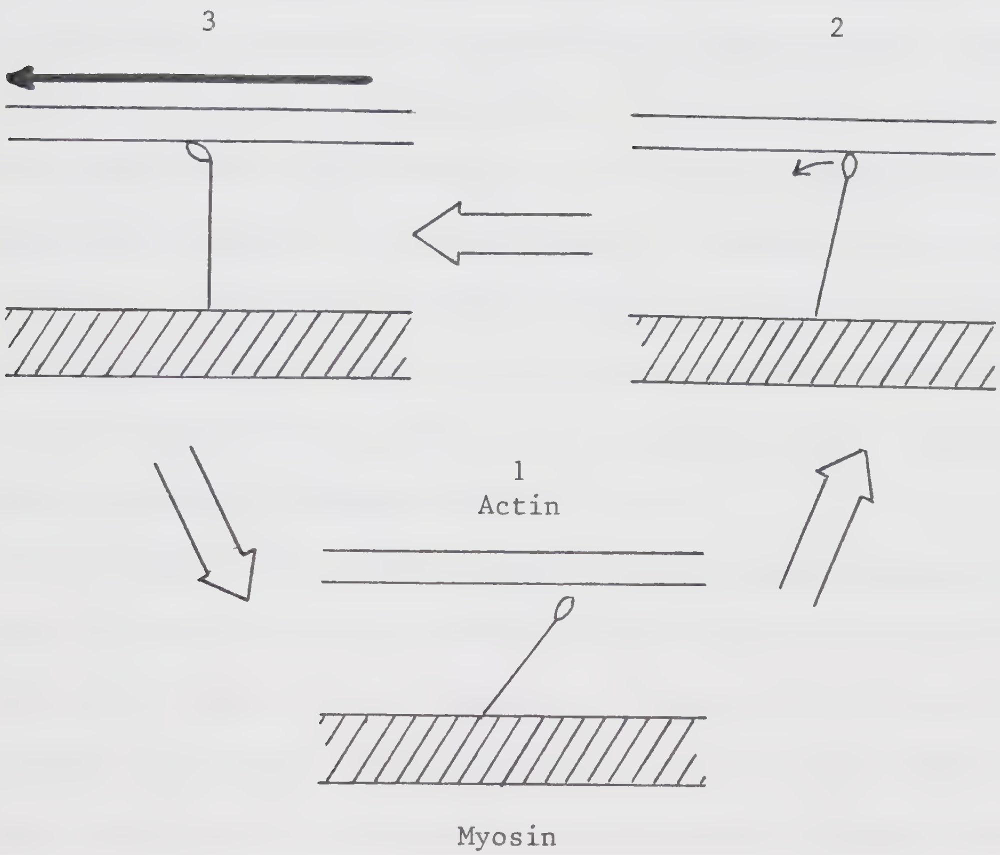

Figure 3 - Actin - myosin cross bridging. Diagram 1 - resting state; Diagram 2 - cross bridge linking; and Diagram 3 - movement of the myosin head.

hence shortening the muscle. The degree of strength developed by the cross bridge movement depends on the overall number of cross bridges operating at one particular time.[21,24]

Each muscle fiber has already been mentioned as containing several thousand myofibrils. Running parallel to the longitudinal myofibrils is an extensive endoplasmic reticulum called the sarcoplasmic reticulum. The sarcoplasmic reticulum consists of microscopic tubules which act as transport and storage facilities for the various substances involved in muscle contraction (calcium being one of these). Perpendicular to the sarcoplasmic tubules are a second set of tubules, the transverse or T tubules. T tubules are present wherever the actin and myosin filaments overlap, hence there are two (2) per sacromere--one (1) at each end, and pass from the outside of each muscle fiber, through to the center, then out the opposite side.[24]

To enable the mechanical shortening of skeletal muscle, an electrical impulse must be passed down the afferent motor nerves supplying the desired muscle. The abundance of nerves in the human body is extremely high with approximately two and a half million fibers travelling to and from the central nervous system. Sensory nerves comprise approximately two million of this total with motor nerves making up the remainder. The ratio of sensory nerves to motor nerves in any one segment of the body varies between 2:1 and 10:1, with the lower ratio reserved for muscle responsible for very fine, precision type movements.[44]

Nerves and to a lesser extent muscle fibers are encased in a polarizable membrane.[50] A difference of potential exists between

the outer and inner surfaces of this membrane. The outer surface of the nerve is surrounded by sodium ions and hence carries a positive charge. The inner surface of the nerve membrane contains a high concentration of protein anions, (which cannot diffuse outside the cell membrane) and potassium ions (held within the membrane by the oppositely charged protein anions).[1] Overall, the number of positive charges is greater outside the nerve membrane than within when the nerve is at rest.[50] Excitation occurs when a mechanical, electrical, or chemical stimulus alters the nerve membrane's permeability to sodium ions hence decreasing the number of positive charges outside the cell walls. The resultant negative state outside the membrane upsets the normal resting potential and depolarization of the nerve occurs.[7]

Once depolarization has taken place, the nerve membrane affected becomes virtually impermeable to sodium ions. The sodium ions isolated inside the membrane are transported back outside via a sodium "pump" and the normal resting potential returns. This is referred to as repolarization.[46]

Once an action potential has been initiated within a motor nerve fiber, the excitation stimulus is carried distally down the fiber to the muscle (sensory nerve stimuli may travel either proximally or distally). Upon reaching the muscle, extracellular fluid around the muscle fibers also depolarizes. The T tubules enable the depolarized extracellular fluid to simultaneously stimulate deep as well as superficial myofibrils.[24]

As the extracellular fluid in the T tubules becomes depolarized, and since the T tubules lie in very close proximity to the bulbous

cisternae of the sarcoplasmic reticulum (Figure 4), stimulation of the sarcoplasmic reticulum occurs causing release of its intracellular components, in particular calcium.[28] Release of calcium enables the contraction to proceed as previously documented. The cycles of cross bridge linking and releasing occur as long as calcium is present to keep the inhibitory tropomyosin strand deep within the F-actin groove. When calcium is no longer present, that is, it has returned to the sarcoplasmic reticulum, the actin-myosin portion of the sacromere must wait for the next excitation stimulus before repeating its contractile action.[21,24]

In response to a single excitatory stimulus as described above, the muscle itself undergoes a very quick twitch. As the frequency of individual excitatory stimulus increases, the muscle innervated has progressively less time between twitches to relax. When the frequency of twitches rises above 20 per second, complete relaxation between each stimulus does not occur and a partial tetany results. At approximately 40 to 60 stimuli or twitches per second, no relaxation occurs and a smooth tetanic contraction results.[24]

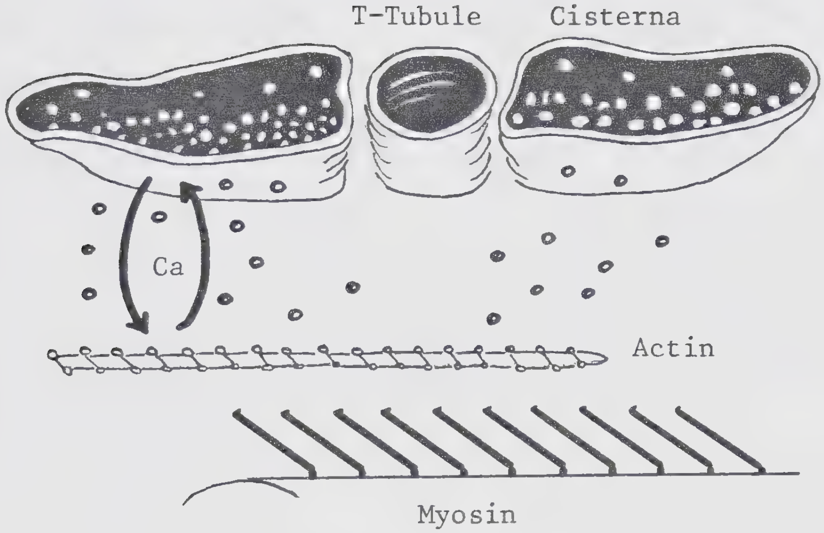

Figure 4 - Sarcoplasmic reticulum and transverse tubules (adapted from Ianuzzo[28]).

B. Initiation of an Actin Potential through External Electrical Stimulation

An electrical stimulus is able to excite a nerve fiber creating an action potential when the stimulus meets certain criteria. That is, the duration of the stimulus is long enough, the intensity of the stimulus is great enough and the rate at which the stimulus builds up to its set intensity is fast enough.[7] The minimum intensity of a stimulus, of sufficient duration, which is just able to excite a nerve is known as the rheobase.[7] Different fibers have different rheobase values. As the intensity of electrical stimulus increases, so too does the number of rheobase levels surpassed, hence more motor units are innervated and a stronger muscle contraction results.[47]

The chronaxie of a nerve is the minimum effective duration time over which an intensity of twice the rheobase acts.[46] The chronaxie is a means of determining the excitability of depolarizable tissue. The smaller the magnitude of the chronaxie, the greater the excitability.[46] The chronaxie of normally functioning human motor nerves is approximately 0.02 milliseconds, while that of muscle and sensory nerve fibers is approximately 1.0 millisecond.[24]

Upon stimulation by whatever means, a nerve fiber undergoes physiochemical changes (depolarization) whereupon no further excitement is possible. This period is known as the absolute refractory period (ARP).[1,46] Immediately following the absolute refractory period, the nerve undergoes a stage of repolarization during which time a

stronger stimulus than original is necessary to evoke an action potential. This period is known as the relative refractory period (RRP).[1,46] Although it varies tremendously for different types and sizes of nerve fibers, the ARP of human nerves is approximately 1.0 millisecond while the RRP lasts a few milliseconds longer. Generally though, the larger the diameter of the nerve, the shorter the ARP and RRP. Some large diameter nerves can recover 90 percent of their normal resting state within 1.0 millisecond.[1] It is the presence of ARP and RRP in nerves which limits the ultimate frequency at which an electrical stimulator can effectively operate.

When a nerve is subjected to an electrical stimulus, it undergoes a phenomenon known as accommodation. Accommodation implies that the threshold or rheobase for excitation of a nerve increases as the stimulus develops. A rapidly developed stimulus is thus more likely to overtake the rising threshold and stimulate the nerve than is a slow developing stimulus, to which the nerve is able to accommodate.[50]

C. Current Qualities of Electrical Muscle Stimulation

As previously mentioned, the presence of absolute and relative refractory periods in nerve fibers limits the effective operating frequency of E.M.S. current. Since the stimulus frequency is restricted, low frequency currents are used to electrically stimulate nerves and by way of nerves the muscles themselves.[50] Low frequency currents are defined as those with a frequency not greater than 1000 Hertz and present by themselves no thermal effect. That is,

they do not contribute to any heat built up within the muscle by direct conduction of the current.[50]

The initiation of an action potential within a particular nerve by external means has already been mentioned as requiring a stimulus of sufficient frequency, duration and intensity magnitudes. In the case of E.M.S. in man, the current must also be tolerable causing minimal sensory nerve excitation.[47] One such current that is used on normally innervated human muscle without complication is faradic current.

Faradic stimulation or faradism originated in 1831 with the invention of the induction coil by Michael Faraday.[36] Although there exists no precise definition of faradic current, it is generally comprised of short duration stimuli (approximately 1.0 millisecond) with interspersed rest periods of near baseline intensity. The rest periods are sufficiently long to limit the frequency of stimulation to approximately 50 to 100 cycles per second.[47]

Faradic current can be supplied in either direct (DC) or alternating current (AC) formats. Often the AC faradic current is comprised of two cycles of unequal phases; the first of low intensity and long duration, while the second is of high intensity and short duration (Figure 5). Nerve depolarization occurs as a result of the stimulatory effect of the second cycle while the first or long duration cycle, travelling in the opposite direction, permits repolarization. Direct current faradic stimulators operate similarly to their AC counterparts except during the rest phase the intensity is zero rather than a low intensity reverse polarity wave (Figure 6). It is thought

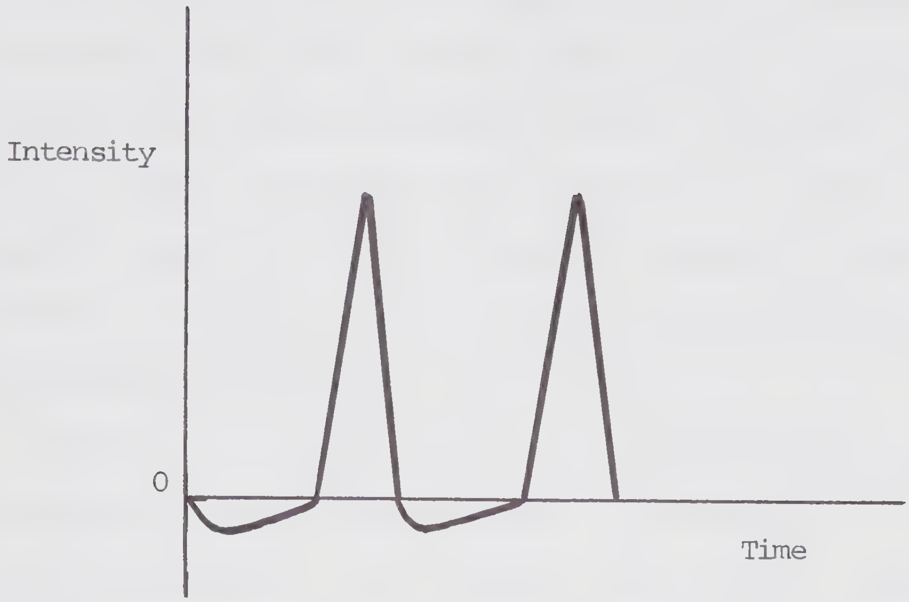

Figure 5 - Unequal phases of faradic Alternating Current.

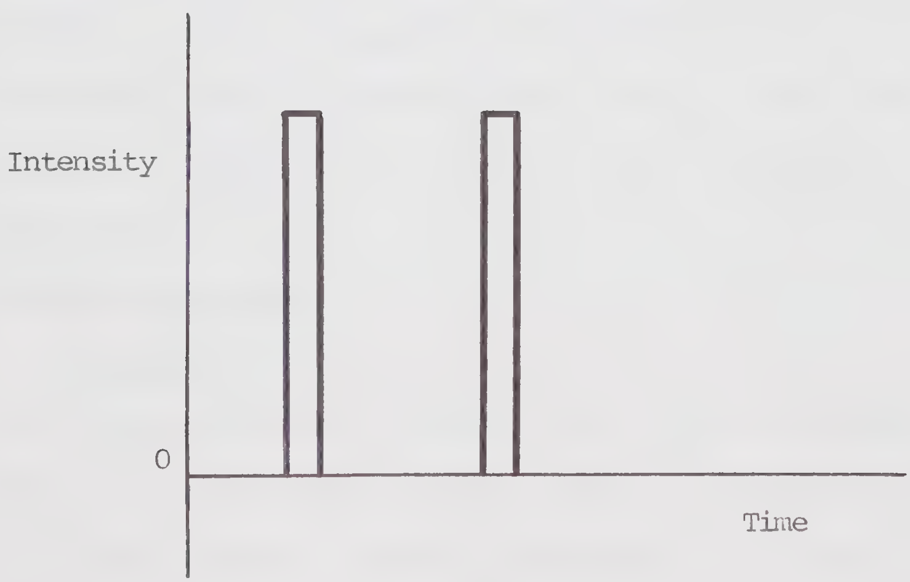

Figure 6 - Direct current faradic wave format

that the reverse or opposite polarity portion of the AC wave, which occurs when the current passes below the zero baseline, reduces or eliminates any chemical ionization buildup in and around the nerve which could cause discomfort in the area being stimulated.[45] Scott[47] claims that the chemical ionization buildup using DC current is negligible if the duration of the excitatory stimulus is kept short (around 1.0 ms).

The most common wave pattern used with DC faradic current is the rectangular or square wave pattern. The advantage of the square wave pattern as compared to the constant rise and fall AC wave is that the square wave does not permit the nerve being stimulated to accommodate to the stimulus.[47] The disadvantage of the square wave as compared to the AC wave, is that square waves undergo much greater phasic distortion as they pass through the tissue resistance. This distortion alters the amplitude and shape of square waves reaching the nerve and may influence the stimulus' ability to excite such fibers. Alternating currents can penetrate tissue resistance with minimal wave form interference.[6,45]

D. Electrode Placement

Electrodes are attached to the skin using electrode pads. Electrode pads are comprised of either felt, cotton or sponge and aide the conduction of electrical current from the electrode to the skin. The skin itself affords a very high resistance to electrical current. This resistant arises from its dry horny texture which contains few ions to pass on the electrical current.[46] To reduce the skin's resistance the area is washed and the electrode pads soaked in a moist

solution, usually water or saline.[46,47,50] This washing and the use of moistened pads not only softens the scaly outer layer of the skin, but also acts to absorb the acid or alkaline byproducts from electrical decomposition of the electrode plate metal; thus preventing chemical burns.[46]

To ensure even concentration of the current through to the skin, the electrode pads must be uniformly moistened (too much moisture is less detrimental than not enough) and the electrode plates must make full and firm contact with the skin.[50]

When positioning the electrode plates, two (2) techniques may be used, namely; indirect or direct.[6]

1. <u>Indirect</u> - the active electrode (cathode), of relatively small pad area, is placed over the main nerve supplying the muscle being stimulated at a point where the nerve is most superficial--thus ensuring optimal excitation. It is the active electrode which initiates the contraction.[50] The larger dispersive electrode (anode) is placed on the same side of the body and proximally to the active electrode. The anode is positioned over an area containing little or no superficial muscle tissue (for example, the sternum or lumbo-sacral area). The larger size of the dispersive electrode reduces its current density concentration, and when combined with the rather boney placement of the pad, ensures minimal contraction of structures beneath this pad.[50]

2. <u>Direct</u> - both eletrodes are of equal size, with the active electrode (cathode) positioned distally on the muscle, while the dispersive electrode is located proximally on the same muscle or functionally related muscle group.[46,50] The direct method ensures

that the current flows longitudinally through the complete length of the muscle. The greater the size of the muscles stimulated, the larger the electrode pads required.[50]

CHAPTER TWO

REVIEW OF LITERATURE

It has been known for centuries that muscle can contract by artificial as well as voluntary means.[36] It has not been until recently however that comparisons between M.V.C. and electrically induced contractions have been investigated. One of the earliest studies comparing forces produced by M.V.C. and E.M.S. was conducted by Merton in 1954. Merton[37] designed an apparatus which permitted isolated contraction of the abductor pollicis in man. Tests were performed to ensure that upon maximal voluntary abduction of the thumb, other muscles, in particular the opponens pollicis, flexor pollicis longus and first dorsal interosseous muscles, did not significantly affect the tension generated. Tension was measured by means of a mechano-electric transducer. The abductor pollicis muscle was chosen for study as it is the only ulnar supplied muscle acting on the thumb and also the only muscle used in voluntary abduction. The author served as the only subject although it was reported that similar results were obtained using other subjects. Although the exact current format used was not described by Merton, it was suspected based on the stimulator model, to be an interrupted direct current of unspecified stimulus duration and wave form. The active electrode was positioned over the ulnar nerve at the wrist. The frequency of E.M.S. was varied between 10 and 50 cycles per second (cps). Results of the study indicated that

tensions generated at the faster stimulation frequences (40 to 50 cps) equalled those obtained from two (2) maximum voluntary contractions. Increasing stimulation voltage beyond that required for matching M.V.C. tension did not further increase E.M.S. tension thus indicating to the author that the contractile mechanism was fully activated. When superimposing E.M.S. on muscle contraction, Merton[37] found that if the voluntary contraction at the time of stimulation was not maximum, then additional tension was generated. The degree to which this additional tension was generated decreased as voluntary tension approached maximum. At no time did tension created by E.M.S. superimposed on voluntary contraction exceed the tension achieved by M.V.C. alone. No statistical analysis was performed on the data.

Bigland and Lippold[3] investigated the proportionality between the mean tension generated by the abductor pollicis and abductor digiti minimi brevis muscles from direct and indirect E.M.S. techniques using different stimulation frequencies. The authors attempted to discover which stimulation frequency was most effective in recruiting the maximum number of motor units. This was accomplished by increasing E.M.S. frequency until no further increase is generated tension occurred thus indicating complete tetany. The current format incorporated square waves of 0.25 millisecond (ms) duration at a frequency varied between 0 and 100 cps. The middle three (3) fingers, palm, wrist and lower arm were rigidly fixed in a plaster case with openings for the thumb and little finger. Strain gauges were used to measure tension. Only one (1) subject participated in the study which required three (3) M.V.C.'s

to be performed followed by E.M.S. contractions at five (5) minute intervals using different stimulation frequencies. Although no statistical analysis was performed on the data, results indicated that the indirect E.M.S. technique stimulating the ulnar nerve at the elbow, produced the same tension as that attained during maximum voluntary contraction. Maximum E.M.S. tension occurred at a frequency between 35 and 40 cps irrespective of the E.M.S. technique used. Further increases in frequency resulted in no further gain and sometimes a drop in generated tension. Pain was the limiting factor in determining the maximum amount of E.M.S. intensity able to be used.

Naess and Storm-Mathiesen,[40] in experiments similar to Merton's[37] examined the fatiguing process associated with M.V.C. and supramaximal stimulation of the abductor pollicis muscle. Supramaximal stimulation involved stimulating the motor nerve of a muscle at a voltage at least 20 percent greater than that needed to achieve a maximal mechanical or electrical response. A constant voltage electronic stimulator was used supplying square wave impulses of 0.5 to 1.0 ms duration and operating at a frequency of either 50 or 200 cps. Stimulation of the abductor pollicis muscle was accomplished using an indirect electrode placement with the active electrode over the ulnar nerve just below the wrist. Six (6) normal subjects participated in the study although most of the data reported were the results obtained on the authors themselves. Although no statistical analysis was performed on the data, the authors did conclude that contractions obtained by E.M.S. were not greater in magnitude or of longer duration than voluntary contractions. The authors also stated that contractions

produced at high frequency (200 cps) were of somewhat larger amplitude than those produced at low frequency (50 cps).

Simonson,[48] in examining the graph recordings from Naess and and Storm - Mathiesen's[40] study, commented that the "fatigue time of voluntary contraction was somewhat longer, while the contraction height with indirect stimulation was greater, suggesting that not all fibers were activated in maximum voluntary effort."

Edwards et al.,[15] while experimenting with the heat production and chemical changes associated with isometric and E.M.S. induced contractions of human quadriceps muscle, were able to demonstrate on one (1) subject that force generated by E.M.S. equalled the same subject's M.V.C. force. A square wave stimulus of 50 microseconds (μs) duration and operating at a frequency of 50 cps was applied to the femoral nerve three (3) to five (5) centimeters lateral to the femoral artery using an indirect electrode placement technique. Strain gauges were used to measure quadriceps force as the subject forcefully extended his knee against a non-elastic strap attached to his ankle. A further discovery made by Edwards et al.[15] on eight (8) subjects and involving 58 voluntary contractions, was that rate of rise of muscle temperature was proportional to the sustained force of contraction. In testing a further 12 subjects, the authors found that rate of temperature rise for M.V.C. and maximal E.M.S. induced contractions were equal, indicating that the amount of force generated in each case was also equal. No statistical analysis was performed on this aspect of the study.

Bigland-Ritchie et al.,[4] in examining the relative contributions of central and peripheral fatigue in sustained M.V.C. of human quadriceps muscle, were able to show on one (1) subject that supramaximal indirect stimulation of the quadriceps via the femoral nerve produced contractile forces equal to the same muscle's maximum voluntary contraction. The current format used was 50 μs duration square waves delivered at a frequency of 50 cps. The subject was seated upright in an adjustable chair with the knee held in a position of 90 degrees flexion. Maximal voluntary contraction and E.M.S. contractile forces were recorded using strain gauges. No statistical analysis was performed on the data.

Bigland - Ritchie et al.[5] compared the changes in electrical activity of the human abductor pollicis muscle during fatiguing M.V.C. and while undergoing equal periods of maximal ulnar nerve stimulation at different frequencies. The muscle's force output, smoothed rectified E.M.G. and area of evoked surface action potential were measured. Indirect stimulation using 50 to 100 μs duration impulses was applied to the ulnar nerve at the wrist. Maximum intensity was set at a voltage 20 percent greater than that required to elicit maximum action potential size. The E.M.S. induced contraction was maintained for 60 seconds with the frequency held constant during this time at either 20, 50 or 80 cps. Force recordings were obtained using a dynamometer modified from Merton.[37] Subjects for the experiment included the investigators themselves and several physicial therapy students; exact numbers were not specified. Though not supported by statistical analysis, the authors did stipulate that E.M.S. at the higher frequencies (50 and 80

cps) produced forces equal to those attained by maximum voluntary contraction.

Jones et al.[32] examined the loss of force that occurred during M.V.C. and E.M.S. contraction of the abductor pollicis muscle. Although not the prime objective of the experiment, Jones et al.[32] did demonstrate that by using 50 µs duration stimuli at a frequency of 80 cps, E.M.S. induced muscle contraction force could equal but not surpass M.V.C. force. The rate of force loss was found to be greater for sustained electrically induced maximal contractions (60 seconds duration) than for sustained maximum voluntary contraction. The testing procedure used on the abductor pollicis muscle was similar to that described by Merton.[37] An indirect stimulation technique via the ulnar nerve at the wrist was used. An additional finding of Jones et al.[32] was that force generated by low frequency E.M.S. (20 cps) equalled only 70 percent of the force generated by high frequency E.M.S. (80 cps), although the low frequency current resulted in less fatigue. No statistical analysis was performed on the data.

In a non experimental report on E.M.S. training, Cafarelli[8] stated that "an electrically stimulated contraction cannot produce more force than a maximal voluntary effort." No mention of how Cafarelli[8] came to this conclusion was made.

Edwards et al.[16] investigated the effects of repetitive E.M.S. to a substantial portion of the quadriceps and to the abductor pollicis muscle over a range of frequencies, on muscular force and the time course for relaxation. Subjects were all normal and healthy although total number incorporated was not mentioned. The quadriceps muscle was

stimulated directly using surface electrodes, while the abductor pollicis muscle was stimulated indirectly by way of the ulnar nerve at the wrist. Stimulation was by unidirectional square wave pulses of 50 μs duration with a frequency of either: 3,5,8,10,15,20,30,50,80, or 100 cps. The intensity of stimulation was limited to 70 volts for the quadriceps and 80 volts for the abductor pollicis. No justification was made by the authors for selection of these particular voltage limits. The E.M.S. current was applied for two (2) to five (5) seconds with 15 to 30 seconds rest between the activity periods. Results demonstrated that quadriceps E.M.S. induced contractile force equalled at best 60 percent of M.V.C. force. The low contraction force was attributed to the surface electrodes inability to stimulate all of the quadriceps available muscle fibers. An E.M.S. induced contraction force from one (1) subject equalled M.V.C. force when the quadriceps muscle was stimulated indirectly via the femoral nerve. No statistical analysis was performed on the data. The M.V.C. force of the abductor pollicis was not reported and hence not compared to E.M.S. force due to the difficulty separating the contribution of this muscle from that of the thumb's long flexor muscles. The apparatus designed by Merton[37] was used to record the thumb's force. The strongest contractile force at the pre-set intensities, for both the quadriceps and the abductor pollicis muscles, occurred at approximately 50 cps whereupon any further increase in frequency caused no further change in the amount of force generated.

Curwin et al.[13] examined the effects of high frequency E.M.S. to the quadriceps of patients who had undergone anterior cruciate

ligament surgery. No mention of the total number of patients incorporated in the study was made. All patients were divided into either a control or experimental group. The control group underwent normal physiotherapy with no E.M.S. while the experimental group underwent the same conditions plus an E.M.S. rehabilitation program. The current format used was a sinusoidal current of 2500 Hertz (Hz) carrier frequency, modulated to an output frequency of 50 Hz. Intensity was set at maximum current tolerated by each individual. The subjective findings of the authors' were: 1) in contrast to Kots'[35] claims that this form of E.M.S. was virtually painless, patients in this experiment experienced pain similar to that produced by severe muscle cramp, and 2) maximal contraction due to this form of E.M.S. was not greater, but in fact less, than maximum voluntary contraction.

Sugai et al.[51] noted that in both Merton's[37] and Bigland and Lippold's[3] studies, comparing M.V.C. and E.M.S. force, pain ultimately limited the intensity of stimulation especially at the higher frequencies used. Even with pain from E.M.S. present, both previous authors were able to duplicate M.V.C. force with electrical muscle stimulation. Sugai et al.[51] also measured force output from the abductor pollicis muscle but only during E.M.S. induced contractions. The subjects in Sugai et al.'s[51] experiment, 19 adult males, all underwent general anaesthesia before the E.M.S. testing. A direct current of 200 μs duration with a frequency varied between 10 and 100 cps was used. Results indicated that with the constant intensity current (set for supramaximal stimulation at 50 cps), maximum tension did not occur until approximately 75 cps. The tension generated at 75

cps was well maintained up to the maximum frequency incorporated, 100 cps.

The results of Sugai et al.'s[51] study contrasted those of Merton[37] and Bigland and Lippold[3] who found frequencies of 50 cps and between 35-40 cps respectively to generate the greatest amount of force. The previous authors found pain to be the main factor limiting current intensity at frequencies greater than 50 cps. Sugai et al.[51] concluded from the results of their study (which eliminated the component of pain) that individuals possessing high pain thresholds may be able to surpass M.V.C. force by using an E.M.S. current frequency of greater than 50 cps.

In a demonstration of how subject pain tolerance limits the amount of E.M.S. current able to be used on a muscle and hence limits the resultant force of contraction, Iddings et al.[29] used five (5) percent benzocaine suspended in calamine lotion to cause local anesthesia. As a control, normal calamine lotion was also used. No mention of the number of control and experimental group subjects was made. A total of nine (9) muscles were examined over 13 to 20 treatment sessions. For three (3) of these muscles, a significant increase (no significance level indicated) in the amount of tolerable intensity was demonstrated. The author also subjectively stated that an increased muscle contraction occurred when five (5) percent benzocaine was used.

Milner et al.[39] investigated the variability which exists between the maximum amount of current tolerated and the resultant maximal E.M.S. contractile force produced for different individuals. A direct, 0.2 ms duration -- 50 cps, current was used. Results showed

that maximum current tolerated by the 11 male subjects varied between 28 and 135 milliamperes while maximum force developed varied over a 17 to 1 ratio. All stimulation was to the quadriceps muscle. The authors claimed that not only was pain tolerance a limiting factor in the final determination of maximum current intensity, but also the "spreading of the effect of the current on nerves and muscle groups other than those for which stimulation was intended."

In a letter describing their previous experiment and results (which had not at that time been published), Milner et al.[38] stated empirically that contractile force from E.M.S. could only equal 40 percent of the same muscle's maximum voluntary contraction.

In a non-English paper by Ikai et al.[30] and quoted in Simonson[48] and Ikai and Yabe,[31] it was found on average of 10 subjects, that contraction force of the abductor pollicis muscle from maximal E.M.S. was 31 percent higher than M.V.C. force. A rectangular wave stimulus of five (5) ms duration--50 cps frequency, was used for stimulating the abductor pollicis muscle. Ikai et al.[30] attributed the discrepency in results between their experiment and those of Merton[37] and Naess and Storm-Mathiesen,[40] who were not able to show any difference between M.V.C. and E.M.S. induced contraction forces, to different active electrode positioning: at the wrist in Merton's[37] and Naess and Storm-Mathiesen's[40] experiments and over the ulnar nerve just lateral to the medial epicondyle in their own study.[48] Since Bigland and Lippold[3] used the same indirect stimulation technique as Ikai et al.,[30] but were still unable to show increased force of contraction using E.M.S., it would appear some

unknown factor was responsible for the difference. Ikai and Yabe[31] commented that subject recruitment for their earlier study was quite difficult due to the very painful nature of E.M.S., indicating that perhaps the authors used current intensities which exceeded subjects' normal tolerance level.

Perhaps the most controversial papers dealing with E.M.S. and its effect on muscular strength are those by Kots[35] and Kots and Chuilon.[34] In experiments on 15 to 17 year old sumo wrestlers, Kots and Chuilon[34] claimed that E.M.S. to the biceps brachii and triceps surae muscle groups resulted in strength gains of between 30 and 40 percent for the biceps and up to 50 percent for the tricep surae after a maximum of 19 treatment sessions. Such high strength gains were attributed according to Kots,[35] to a failure of normal M.V.C. to recruit the maximum number of motor units available. Kots[35] claimed that E.M.S. induced maximal contractions produced forces 10 to 30 percent greater than that generated by maximum voluntary contraction. Biemann[2] claimed that the E.M.S. current employed by the Soviets was a 1600 Hz sinusoidal current modulated to an output frequency of 50 Hz. Due to the fact that all of Kots' work was written in Russian and thus required English translation, not all the methodology or statistical design information was available. For this reason, the unsubstantiated claims made by the Soviet author must be viewed with caution. Also, the rather young age of Kots' subjects suggests that maturation could partly explain some of the increases attained over the three (3) to four (4) week training period.[9]

The question of whether E.M.S. can contract a muscle with greater force than M.V.C. has not been resolved in the review of past related literature. Many of the past studies were performed by Neurologists whose primary intention was the investigation of facets other than the direct comparison of E.M.S. force with M.V.C. force. Additionally, none of the results of past studies were subjected to statistical analysis -- limiting the credibility of any respective implications.

The controversy surrounding the Soviet study of Kots and Chuilon[34] if nothing else, has done much to promote or rekindle interest in electrical stimulation. If a muscle can contract more forcefully using E.M.S., as the Soviets claim, the implications to the field of strength training are immense.

CHAPTER THREE

METHODOLOGY

I. SUBJECTS

The subjects used in this study were healthy volunteers with no known pathological condition(s) which may have been exacerbated by the experimental procedure. Subjects reporting any form of right knee or hip surgery prior to this investigation were not included in the study.

A total of 32 male subjects volunteered for the study. Two (2) subjects were not able to complete the experimental procedure, leaving a total of 30. Each of the 30 subjects was randomly assigned to one (1) of three (3) groups; each group using a different current format (E.M.S. unit). Once assigned to an E.M.S. group, each subject was randomly assigned a sequence order in which he was to perform the different maximal contraction conditions. The three (3) different contraction conditions were: 1) M.V.C., 2) E.M.S. only, and 3) combined maximal contraction (C.M.C.) — M.V.C. with superimposed maximally tolerated electrical muscle stimulation.

II. MEASUREMENT APPARATUS

The instrument used for measuring quadriceps torque consisted of a special knee extension dynamometer capable of measuring both isometric and isokinetic torque.[49] The dynamometer consisted of a chair and adjustable lever arm connected to the output shaft of a 1:600 gear

reduction box. The gear box's input shaft was connected to a reversible half horse-power electric motor, which in this experiment was used simply to move the lever arm to the desired testing angle -- 60 degrees from horizontal. A testing angle of 60 degrees was used since maximum knee extensor torque occurs between 50 and 70 degrees of knee flexion.[25] Four (4) SR-4 type strain gauges were positioned on the lever arm, 11.5 cm from its axis of rotation. The chair was adjustable for seat height and length and incorporated an upright back rest and seat belt for securing the subject comfortably while minimizing extraneous movement.

The four (4) SR-4 strain gauges, interconnected to form a Wheatstone Bridge (Figure 7), were mounted on the lever arm so that at rest the resistance across one side of the bridge (strain gauge 1 and strain gauge 4) equaled the resistance across the other side of the bridge (gauges 2 and 3 respectively). When connected in this fashion and provided the internal resistance within each gauge was equal, the Wheatstone Bridge was balanced and no pen drift was observed on the recorder. As soon as force was exerted on the lever arm, the resultant strain deformed the strain gauges and altered their internal resistance resulting in a measureable voltage change across each side of the bridge. The amount of change in the resistance of the strain gauges was calibrated to have a direct linear relationship with the amount of strain incurred by the lever arm metal.

The 15 volt signal input to the strain gauges was supplied by a DC strain gauge force coupler with an inbuilt balance control to equalize the resting resistances across each of the strain gauges comprising the

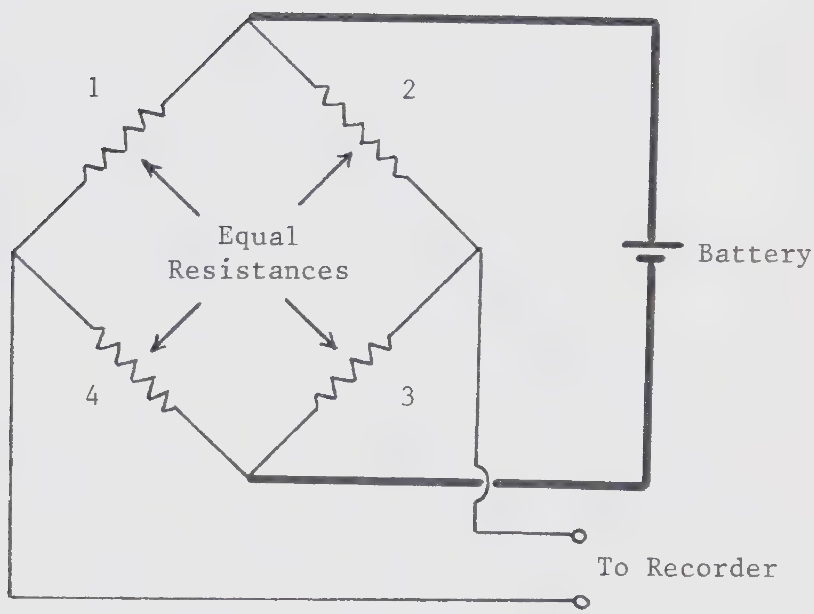

Figure 7 - Wiring of strain gauges to form Wheatstone Bridge.

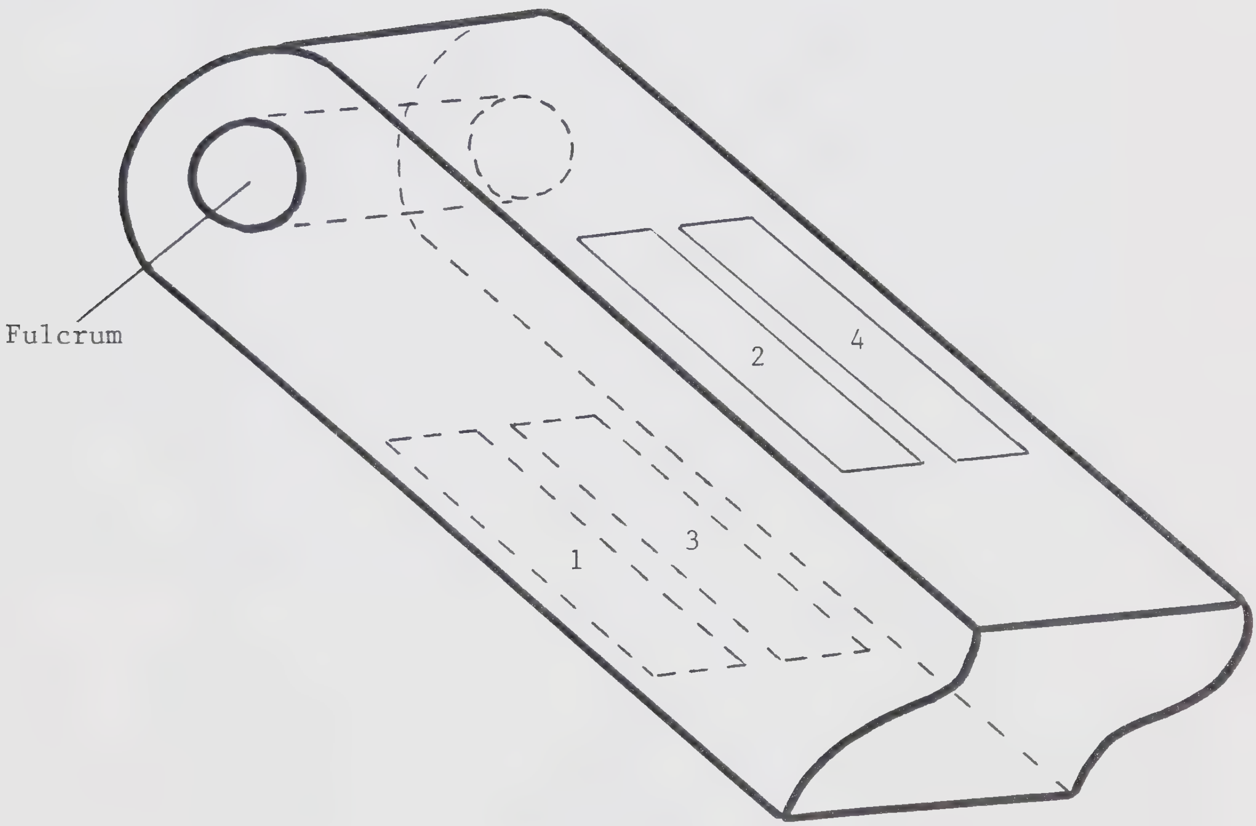

Figure 8: Positioning of strain gauges on lever arm metal.

Wheatstone Bridge. A Beckman paper recorder was used to provide a permanent record of all torques (Figure 9). The recordings obtained from the Beckman recorder represented the resistance torque provided by the dynamometer to match the contractile torque produced by the subjects' quadriceps muscles.

III. CALIBRATION

Calibration of the dynamometer was accomplished by rotating the lever arm to a horizontal position. Weights of 22, 44, 66 and 88 kilograms were alternately positioned on the lever arm at a distance of 0.45 meters from the fulcrum, thus representing torques of 10, 20, 30 and 40 kilogram meters respectively. The subsequent sensitivity governing the deflection of the paper recorder's pen was adjusted so that 15 divisions on the recording paper represented 10 kilogram meters of torque. Calibration of the dynamometer was performed at the beginning and end of each testing day.

IV. TESTING PROCEDURE

As previously described, the 30 volunteer subjects were randomly divided into three (3) different groups; each group using a different current format. The order that the maximal contractions were to be performed was also randomly assigned. A random number chart was used to ensure randomization. Four (4) trials of each contraction condition were performed by each subject and recorded. A total of 12

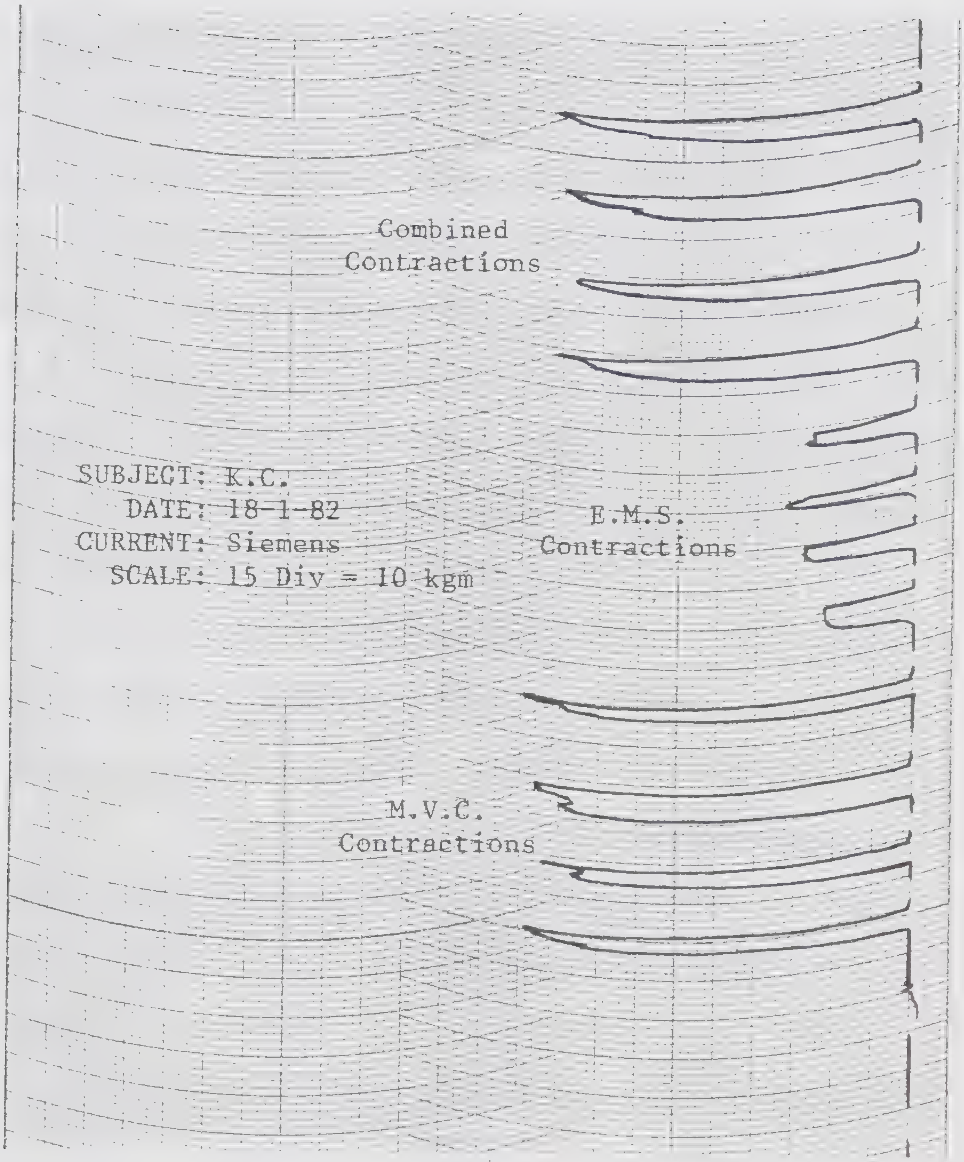

Figure 9: Torque readout illustrated by Beckman paper recorder.

maximal contractions per subject per test session were thus recorded.

To familiarize subjects with the testing procedure and the sensation of E.M.S., each was required to participate in two (2) practice sessions prior to the actual test session. Two (2) full days without stimulation were provided between the first and second practice sessions and between the second practice session and the test session.

The first practice session involved explaining to the individuals the purpose and procedures of the study, the risks and obligations involved, and the perceived sensation of electrical stimulation. Consent forms were read, signed and collected during the first practice session. The final part of the first practice session involved a total of 10 M.V.C. and maximal E.M.S. type contractions.

To commence the 10 isometric contractions, the surface electrodes were attached to the subject using the indirect pad placement technique. The indirect stimulation technique was used since it enabled complete and simultaneous stimulation of all muscles comprising the quadriceps muscle group.[16] The seven (7) by seven (7) cm active electrode (negative polarity) and pad were positioned over the femoral triangle of the right thigh. The center of the electrode was directly over the major nerve innervating the quadriceps muscle (femoral nerve). The femoral nerve had been located using an electrode probe of one (1) cm diameter. The active electrode was held in place by the subjects right hand. The 9 by 12 cm dispersive electrode and pad were positioned over the flat boney lumbo-sacral area and held in place by a tensor bandage.

All electrode pads were left soaking in clean water when not in use and excess moisture was squeezed out prior to placement on a subject.

The same electrode plates and pads were used for the Siemens and Medelco units (Appendix 7). Due to the type of electrode connection on the TECA unit, dedicated pads were required. The size of all pads was identical (7 x 7 cm active electrode, 9 x 12 cm dispersive electrode).

After the electrodes were applied, the subject was properly seated into the torque measuring apparatus. The height of the chair was adjusted so that the rotational axis of the dynamometer corresponded with the right knee's transverse rotational axis. The upright seat back (ensuring 90° of hip flexion) was positioned so that the back of each subject's knee just touched the leading edge of the padded seat. The resistance lever arm pad, against which the lower leg pushed, was adjusted so that the bottom of the pad just touched the top of each subject's instep when the ankle was in a fully dorsiflexed position.

Once the subject was correctly positioned on the torque measuring chair, the following procedure was used for the first practice session:

1. The paper recorder was positioned so that the subject could witness all torque outputs. The subject then initiated a M.V.C. which was used as a comparative index for judging subsequent E.M.S. contractions. A 50 second (sec) rest period followed the maximum voluntary contraction.

2. After the 50 sec rest, the subject was instructed to very slowly increase the E.M.S. current intensity to familiarize himself to the sensation. No emphasis was placed on obtaining maximal torque output from this first E.M.S. practice contraction. A rest period of approximately five (5) times longer than the contraction period followed the E.M.S. contraction.

3. The E.M.S. current was increased at a moderate rate until contraction of the quadriceps commenced. At this point the subject initiated a M.V.C. while continuing to increase the E.M.S. intensity until a maximally tolerated level was reached. A 50 sec rest period followed this contraction and all subsequent contractions.

4. E.M.S. only was used and the subject was encouraged to increase the intensity at a moderate rate (to obtain the maximum effect before fatigue set in) until a maximally tolerated level of current was reached.

5. M.V.C. plus E.M.S. to maximum intensity tolerated.

6. E.M.S. only, to maximum intensity tolerated.

7. M.V.C. plus E.M.S. to maximum intensity tolerated.

8. E.M.S. only, to maximum intensity tolerated.

9. M.V.C. plus E.M.S. to maximum intensity tolerated.

10. E.M.S. only, to maximum intensity tolerated.

With the exception of the first E.M.S. only contraction, all contractions required between three (3) and five (5) seconds to complete.

The first practice session was soley designed to familiarize subjects with electrical muscle stimulation. In order to minimize subject apprehension and avoid possible attrition, all subjects were intially exposed to the most "sensation free" current. It was judged by the investigator from pilot work that the TECA unit supplied the least perceivable current.

The second practice session and the test session used the same apparatus set up as in the first practice session except the subject's randomly assigned E.M.S. unit was used plus the paper recorder was removed from the subject's vision. As previously indicated, the second practice session and the test session involved four (4) trials of each of the three (3) contraction conditions.

When M.V.C.'s were to be performed, the subject was advised to increase the force of contraction at a moderate rate up to maximum and hold it there for two (2) to five (5) seconds. Two (2) to five (5) seconds was found by the investigator to be long enough to ensure that a maximal contraction had indeed occurred and further increases in force were not possible.[16] A total of four (4) M.V.C.'s were performed with 50 seconds rest between each contraction. The sequence of maximal contractions of not longer than 10 seconds followed by 50 seconds of rest was suggested by Kot and Chuilon[34] to permit maximal effort with minimal fatigue interference, even after 10 repetitions.

When E.M.S. only maximal contractions were performed, the subject himself controlled the current intensity. The investigator remained with his finger on the E.M.S. unit's on - off button in case problems were encountered. The subject was instructed to relax his right leg and not consciously attempt any voluntary effort at all. Following a signal from the investigator the subject turned the stimulator intensity up at a moderate rate (the same as in the practice trials) until the maximum level of tolerable intensity was reached. The intensity level corresponding to the maxmimum amount of current tolerated was held long enough to enable the investigator to decide that the force of contraction had indeed leveled off (two (2) to four (4) seconds). Four (4) E.M.S. only trials were performed with 50 seconds rest between each trial.

The standard Medelco Ultra Pulsator Model 4 unit incorporated six (6) separate intensity dials, three (3) of which could simultaneously and cummulatively affect one (1) active electrode. In order

for the subject to control current intensity through a single dial, the three (3) intensity channels were connected to a rotary dial rheostat.

When C.M.C.'s were to be performed, the E.M.S. current was increased initially until contraction of the quadriceps commenced. Approximately two (2) seconds were required for this whereupon the subject initiated a M.V.C. while continuing to increase the E.M.S. current until the intensity reached the maximum tolerated. Total contraction time was four (4) to ten (10) seconds. Four (4) C.M.C. trials were performed by each subject with 50 seconds rest between each trial.

The time required to perform each of the two (2) practice sessions and the actual test was between 12 and 15 minutes. The total time required for all aspects of each of the three (3) sessions, including instruction and equipment set up and dismantle was 30 minutes.

Subjects were required to complete an open answer questionnaire after completing the test session. Subjects completed the questionnaire prior to witnessing any results.

Reliability and validity measures of the test procedure and measurement apparatus were calculated and reported in Appendix 4 and Appendix 5 respectively.

V. ELECTRICAL MUSCLE STIMULATORS

The three (3) current formats examined in this study were from therapeutic muscle stimulators designed for use on normally innervated muscle. The means by which each modality stimulated normally innervated muscle varied from unit to unit. As a result of the variations in current qualities between the different units, each was evaluated for its contractile influence on the quadriceps muscle. Although each of the E.M.S. units enabled slight current format variation, the current format used for this study was the one generating the most torque during pilot work. The E.M.S. units and corresponding current formats used in this study were as follows:

	STIMULATOR	CURRENT FORMAT
1.	TECA SP 5/T*	AC Faradic current, 1.0 ms duration stimulus, 100 cps
2.	MEDELCO ULTRA PULSATOR* MODEL 4	AC Biphasic Faradic Current, 0.2 ms duration stimulus, 100 cps
3.	SEIMEN NEUROTON*, MODEL 627	DC Faradic current, 2.0 ms duration stimulus, 45 cps.

*Denotes registered trademark

VI. STATISTICAL DESIGN

The design of this study required all 30 subjects to be randomly assigned to one (1) of three (3) groups (n=10); each group using a different current format. Ten subjects per group provided sufficient power for this particular statistical design.[53] Each subject was also randomly assigned the order in which they were to perform the three (3) contraction conditions (M.V.C., E.M.S. only, and C.M.C.). The dependant variables of the study were; the maximum torque produced by the different contraction conditions and the different current formats. A three-way analysis of variance with repeated measures on subject trials and the type of muscular contraction performed, was applied to the data to determine significant differences. A Scheffe post hoc test was subsequently used to determine where any significant differences lay. The $p < 0.05$ level of significance was adoped throughout the study. All computations for determining significant differences were performed by computer (MTS/SPSS program).

CHAPTER FOUR

RESULTS

The results of the study, summarized in Table 1, were statistically analyzed using a three-way analysis of variance (ANOVA)(Table 2). The three-way ANOVA showed the significant interaction: groups undergoing stimulation from different current formats (A), by contraction condition (B); $F_{AB}(4,54)=7.637, p < 0.001$. The three-way interaction of current formats (A), contraction conditions (B), and trials (C) was not significant at the $p < 0.05$ level of significance, thus, eliminating the need for the calculation of simple main effects.

A Scheffe post hoc comparison between ordered means was employed on interactions demonstrating a significant F ratio. Post hoc comparisons of mean torque generated by subjects stimulated by the TECA current format showed that under M.V.C., E.M.S. only and C.M.C. contraction conditions there existed no significant differences ($p < 0.05$).

In contrast to the above finding, subjects stimulated by either the Siemens or Medelco current formats generated significantly less torque ($p < 0.05$) under the E.M.S. only contraction condition than in respective M.V.C. or C.M.C. contraction conditions. No significant differences ($p < 0.05$) were found between M.V.C. and C.M.C. contraction condition mean torques for either Siemens or Medelco stimulated subjects.

Further post hoc comparisons were made on mean torques generated by subjects in each current format group under the three (3) contraction

conditions. As illustrated in Figure 10, significant differences in mean torque scores were found within the E.M.S. only contraction condition ($p < 0.05$). Under this condition, subjects stimulated with the Siemen's current format generated significantly lower mean torque than subjects stimulated by either Medelco or TECA units. Subjects stimulated by the Medelco current format generated significantly less mean torque in the E.M.S. only contraction condition than subjects using the TECA unit.

TABLE I

Combined Interation Means and Stands Deviations of Current Formats (A), Contraction Condition (B) and Trials (C).

CURRENT FORMATS

CONTRACTION CONDITION (B)	TRIAL (C)	TECA	MEDELCO	SIEMENS	MEAN
M.V.C. Torque (kgm)	1	25.15 (4.59)	25.75 (5.05)	26.85 (4.66)	25.92 (4.98)
	2	25.30 (4.77)	26.05 (5.55)	25.80 (4.46)	25.72 (4.77)
	3	25.10 (4.78)	25.35 (5.72)	26.30 (4.64)	25.58 (4.92)
	4	25.30 (4.35)	25.40 (5.13)	25.95 (4.93)	25.55 (4.66)
	Mean	25.21 (4.44)	25.64 (5.38)	26.23 (4.50)	25.69
E.M.S. Torque (kgm)	1	22.45 (4.69)	17.60 (8.99)	13.45 (9.11)	17.83 (8.47)
	2	23.85 (4.89)	17.80 (8.84)	14.10 (9.17)	18.58 (8.63)
	3	23.55 (4.91)	16.70 (8.24)	13.95 (8.08)	18.07 (8.11)
	4	23.85 (4.59)	16.85 (7.98)	14.05 (8.74)	18.25 (8.22
	Mean	23.43 (4.59)	17.24 (8.20)	13.89 (8.50)	18.18
C.M.C. Torque (kgm)	1	24.90 (4.84)	22.95 (6.37)	26.20 (5.69)	24.68 (5.62)
	2	25.00 (4.48)	23.40 (5.79)	25.90 (4.78)	24.77 (4.98)
	3	24.90 (4.01)	23.50 (5.10)	27.40 (5.19)	25.27 (4.91)
	4	25.10 (4.92)	23.80 (5.82)	27.10 (5.47)	25.33 (5.40)
	Mean	24.98 (4.40)	23.41 (5.56)	26.65 (5.15)	25.01

TABLE II

Three - Way Analysis of Variance Summary Table of Current Formats (A), Contraction Conditions (B), and Trials (C).

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	Probability
A	448.008	2	224.004	0.712	0.500
S-Within	8495.125	27	314.634		
B	4138.945	2	2069.473	38.189	0.001*
AB	1655.352	4	413.838	7.637	0.001*
BS-Within	2926.250	54	54.190		
C	3.008	3	1.003	0.839	0.476
AC	14.883	6	2.480	2.075	0.065
CS-Within	96.813	81	1.195		
BC	18.594	6	3.099	1.456	0.196
ABC	17.656	12	1.471	0.692	0.758
BCS-Within	344.688	162	2.128		

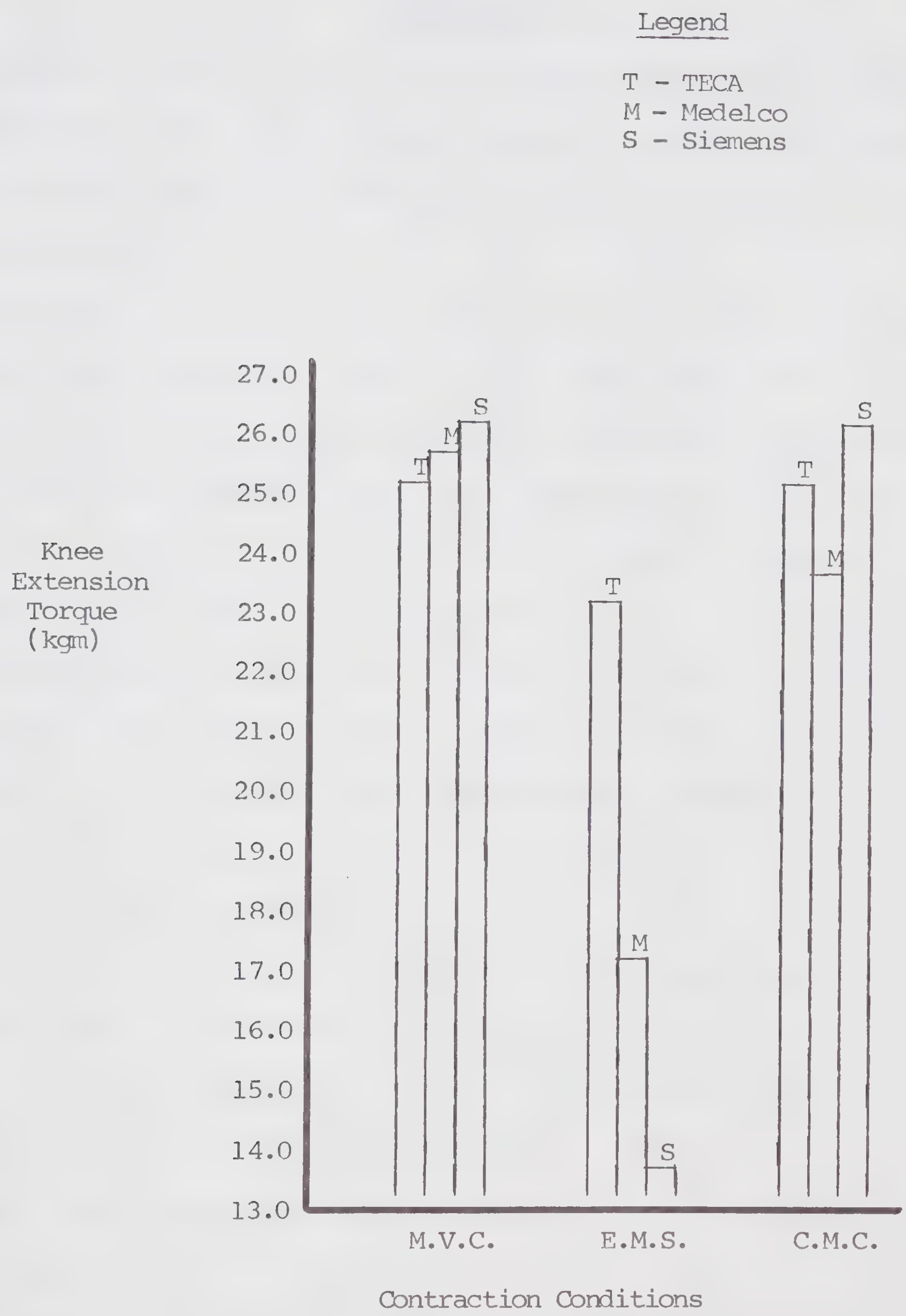

Figure 10: Quadriceps knee extension torques for M.V.C., E.M.S. only, and C.M.C. contraction conditions, using current formats from the TECA, Medelco and Siemens E.M.S. units.

CHAPTER FIVE
DISCUSSION

Based on the results from the statistical analysis, rejection of the first two (2) null hypotheses (listed in Chapter One) and failure to reject the third null hypothesis was warranted at the $p < 0.05$ level of significance.

The first null hypothesis, stating that the mean knee extension torques generated under, M.V.C., E.M.S. only, and C.M.C. were not significantly different from each other, was rejected on the basis of the significantly reduced E.M.S. only mean torques ($p < 0.05$) for subjects using the Medelco and Siemens current formats as compared to their respective M.V.C. and C.M.C. mean torques (Figure 10). As a result of the above finding, it was suggested that E.M.S., when used alone or in conjunction with simultaneous M.V.C. did not recruit more motor units, resulting in a stronger force of contraction, than maximum voluntary contraction. In fact, depending on the E.M.S. unit used, fewer motor units were frequently employed.

Subjects stimulated by the TECA current format were the only subjects able to generate E.M.S. only mean torque equal in magnitude to their respective M.V.C. mean torque. This finding using the TECA current format was in agreement with the non-statistical results of Bigland and Lippold[3], Bigland-Ritchie et al.[4], Bigland-Ritchie et al.[5], Edwards et al.[15], Jones et al.[32], Merton[37], and Naess and Storm-Mathiesen.[40] The inability of subjects using

the Medelco and Siemens units to match their respective M.V.C. mean torques, during the E.M.S. only contraction condition was supported in the literature by Cafarelli[8], Curwin et al,[13] and Edwards et al.[16] The observation that the C.M.C. contraction condition equalled but did not surpass M.V.C. mean torque agreed with the findings of Merton.[37]

The second null hypothesis listed in Chapter One stated that no significant difference ($p < 0.05$) existed between the different current format groups under the same contraction conditions. Rejection of this hypothesis was based on the observation that subjects stimulated by the TECA current format generated significantly more mean torque ($p < 0.05$) in the E.M.S. only contraction than subjects using one of the other E.M.S. units. Furthermore, subjects stimulated by the Medelco unit generated a significantly higher mean E.M.S. only torque ($p < 0.05$) than subjects using the Siemens unit.

The finding that not all E.M.S. units generated the same amount of E.M.S. only torque, has not been reported in the available literature to date. Since all experimental conditions, with the exception of current format and the maximum administrable intensity accepted by the subject or available on the E.M.S. unit, were kept constant for all groups, it was postulated that it was these factors which were responsible for the differences demonstrated.

The TECA unit incorporated an alternating current of 100 cps and a stimulus duration of 1.0 ms. The wave pattern emitted by the TECA unit, as measured on an oscilloscope and illustrated in Figure 11, was distinct from the wave patterns emitted by the Medelco or Siemens units.

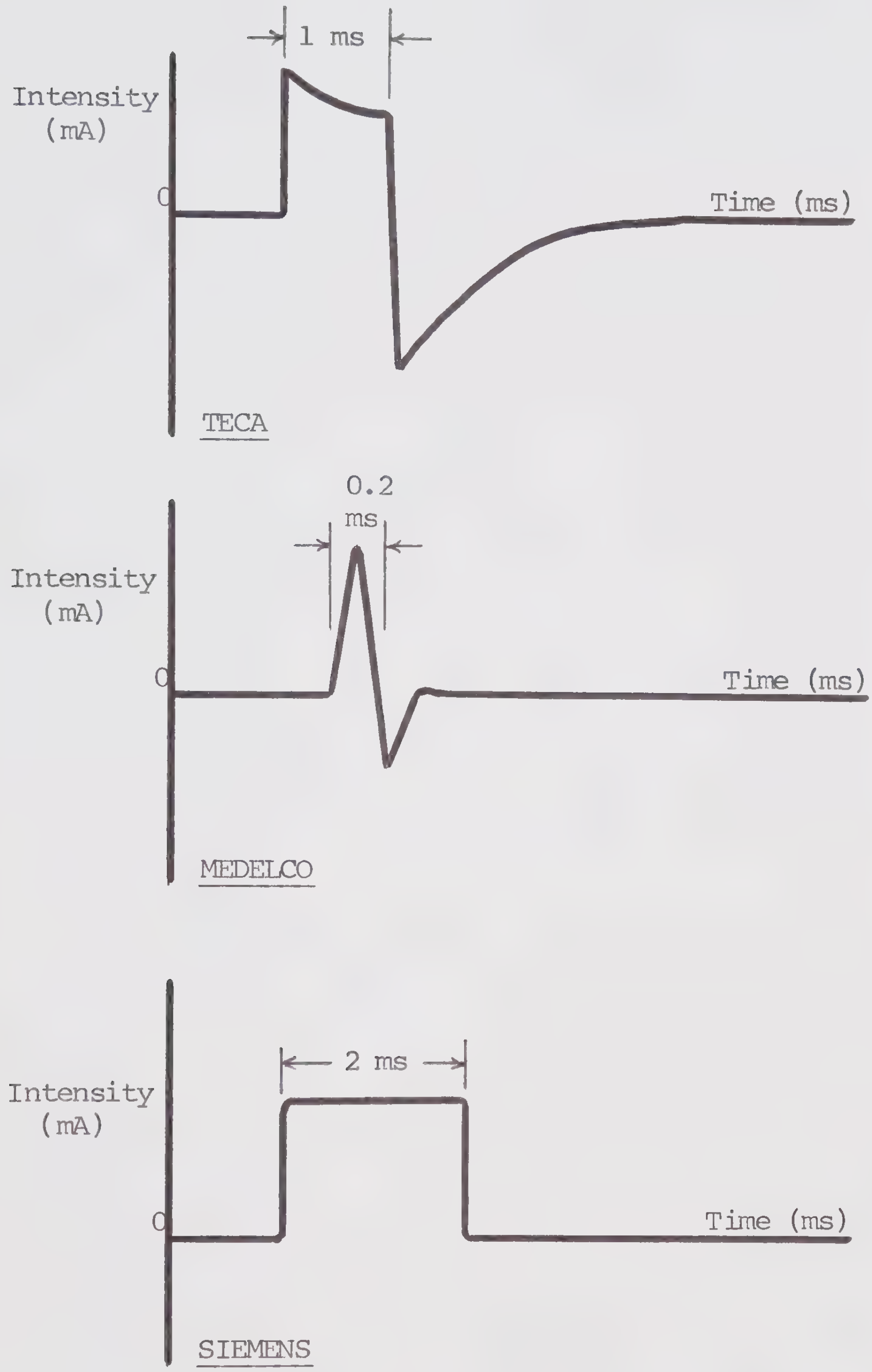

Figure 11 - Comparison of the wave formats from the TECA, Medelco and Siemens E.M.S. units.

The Medelco unit also utilized an alternating current of 100 cps except the stimulatory wave duration was 0.2 ms long. The wave pattern used by the Medelco, as described by the unit's manufacturer, was a "fully de-ionized, spiked biphasic" wave format.[2] The biphasic wave format, shown in Figure 11 was essentially a 0.2 ms duration high intensity spiked wave followed by a similarly peaked reverse polarity wave. The biphasic wave format was advertised as having "an extremely low electrode - skin resistance" enabling "muscle stimulation with currents of high intensity to be carried out without painful burning sensation experienced by the patient under the electrodes."[2]

The Siemens E.M.S. unit comprised the only direct current faradic stimulator in the study. The Siemens unit utilized a 2.0 ms duration stimulatory wave delivered at a frequency of 45 cps. The stimulatory wave was shown to be square when examined on an oscilloscope (Figure 11).

The TECA current format not only provided the highest generated mean E.M.S. only torque of any of the current formats investigated (equal to M.V.C. and C.M.C. mean torque) but did so in a manner combining high intensity with minimal subject discomfort as judged from the response of subjects to the post test questionnaire (Appendix 1).

When subjects were asked "Did you feel you were at as high an intensity level as could be tolerated?" 80% of subjects using the TECA unit (abbreviated T.S. to indicated TECA Subjects) indicated that they

were, while 77% of subjects using the Medelco unit (M.S.) responded affirmatively. Only one (1) subject using the Siemens unit (S.S.) indicated that he was at his maximum tolerable intensity level. When asked to comment on the limiting factor preventing further intensity increase, 40% of T.S. listed subjective factors such as pain or apprehension compared to 50% of Medelco subjects. Fifty percent of T.S. meanwhile, listed physiological factors such as fatigue and the maximum tolerable contraction force within the muscle as reasons for halting intensity progression. No subjects from groups stimulated by either the Medelco or Siemens current formats indicated physiological limitations similar to the above. The E.M.S. unit's maximum administrable intensity was the limiting factor in all 10 S.S. cases, in 50% of M.S. cases, and in only 20% of T.S. cases.

Based on subjects' reaction to the different E.M.S. curents, the TECA current format was the most successful in combining high intensity with minimal adverse affects (for example; pain).

The mean E.M.S. only torque was shown to be significantly less ($p < 0.05$) for the Medelco current format as compared to the TECA current format. Based on the responses of M.S. to the questionnaire, it would appear that the reason for such a significant reduction was two-fold. First, a greater percentage of M.S. indicated that they were limited by the Medelco unit's maximum administrable intensity (50% as compared to 20% for the TECA unit), and second, there was a greater incidence of pain experienced by M.S. as compared to T.S. (40% versus 30% respectively).

Although the difference in the percentage of subjects limited by pain was small between the TECA and Medelco stimulated groups, it was the experience of this author, based empirically on pilot, practice and test session observations, that subjects were more aware of the Medelco current than the TECA current. Furthermore, it was observed that high intensity stimulation from the Medelco unit could not be carried out without painful, burning sensations being experienced by most subjects.

One (1) discrepency evident in M.S.'s responses to the first two questions, which also materialized in S.S.'s responses, was that 7 of 10 M.S.'s indicated that they did in fact receive as much current from the unit as they could tolerate. However, in response to the second question, five (5) subjects stipulated that the inability of the unit to deliver more current was the limiting factor in the determination of maximum tolerance level (for S.S., the numbers were 1 and 10 respectively). The type of subjects used in the study may have contributed to this discrepancy. University Physical Education students comprised a large portion of the sample population. It is possible these subjects were highly motivated and although they felt the muscle was contracting maximally at the unit's maximal administrable intensity, had more intensity been available these subjects would have attempted to go higher.

The response of S.S. to the first two (2) questions on the questionnaire provided valuable insight into why this group performed so poorly in comparison to the other two, in the E.M.S. only contraction condition. The fact that 90% of S.S. did not feel they were at as high an intensity level as could be tolerated and all 100% indicated that it was the unit's limited current output which prevented them from accepting more current,

suggested that it was the Siemens unit's lack of intensity output which resulted in the low E.M.S. only torque magnitudes. It had previously been mentioned that for an electrical stimulus to excite a nerve, and by way of the nerve -- the muscle itself, certain criteria must be met. The stimulus must be of sufficient duration, high enough intensity, and rise to its set intensity at a rate fast enough to minimize nerve accommodation.[7] Although the intensity of each E.M.S. unit was sufficient to initiate quadriceps contraction, it was apparent that some stimulators supplied higher intensity levels, enabling greater numbers of nerve rheobase levels to be surpassed and hence greater force of contraction, than others. Of all stimulators used in this study, the unit's maximal administrable intensity limited the E.M.S. only contraction in 100%, 50% and 20% of cases for the Siemens, Medelco and TECA units respectively. Based on the above, it would subjectively appear that the TECA unit provided the most current intensity followed by the Medelco and the Siemens units. To objectively assess (post testing) the maximal intensity available for each E.M.S. unit, a voltmeter was connected to the electrode leads and the unit's intensity dial turned to the maximum setting. The maximum voltages supplied by the different units were as follows: 1) Medelco - 22.5 Volts, 2) TECA - 11.0 volts, and 3) Siemens - 6.0 Volts.

The objective observation that the Medelco followed by the TECA and Siemens repectively supplied the most voltage differed with the subjective finding based on the number of subjects able to reach the units' maximal administrable intensities and the resultant mean E.M.S. only force of contractions. It is suggested based on the above that the composition

of the different current formats (for example, wave form, stimulus duration or frequency) and not the maximum intensity output primarily determined the extent of the stimulus' effect on the quadriceps muscle. This suggestion is further supported by the fact pain perception varied from current format to current format, with the Medelco registering the highest percentage of subjects limited during stimulation by pain. Although maximum intensity output may not be the most important influence on resultant force of contraction it still appears to be a significant contributor based on the low maximum voltage output and corresponding low mean E.M.S. only torque demonstrated by subjects stimulated by the Siemens current format.

Overall, it would appear that the inherent success T.S. demonstrated in generating the highest mean resistance torque was attributable to both a favorable current format and a sufficiently high maximal adminstrable intensity.

Perhaps the most surprising questionnaire responses were those pertaining to the third question: "Based solely on the sensation within the muscle, did you feel electrical muscle stimulation produced a stronger, equal or weaker contraction than maximum voluntary contraction?" The T.S. were the only subjects under the E.M.S. only contraction condition to record the same mean torque magnitude as M.V.C., however, 80% of these subjects felt their E.M.S. only contraction was in fact stronger than their M.V.C. contraction. Although the E.M.S. only mean torque, using the Medelco current format, was found to be significantly less ($p < 0.05$) than M.V.C. mean torque, 60% of these subjects felt that the E.M.S. only contraction was stronger. The Siemens current format was associated with

the least amount of torque in the E.M.S. contraction condition yet even 40% of these subjects indicated that E.M.S. contraction felt stronger.

In reviewing the above subject responses, it is possible that here lies the answer why scientists and particularly athletes and coaches continue to investigate the field of E.M.S. in light of limited supportive publications advocating its use. It is difficult to theorize why subjects felt E.M.S. only contraction to be stronger than M.V.C. even with units generating relatively low intensity levels (for example; the Siemens 627), however, it is suggested that sensory perception was not the same during the two (2) contraction types. Certainly further investigation of this phenomenon is warranted.

The final question asked of subjects had ramifications for the use of E.M.S. as a strength training modality. It was conjectured that by performing E.M.S. and M.V.C. simultaneously, not only would a complementary effect have been present, but also subjects would not have been as conscious of the electrical current (since some preoccupation would have gone into performing the maximum voluntary contraction). It was suggested that such preoccupation would have resulted in less apprehension, and a higher current intensity level would have been tolerated. A higher current tolerance level was thought to co-incide with enhanced contractile performance. Although subjects were quite unanimous in suggesting C.M.C. permitted what was felt to be more intensity, or an easier tolerance of a unit's maximum intensity, and a stronger contraction, the statistical analysis showed M.V.C. and C.M.C. mean torques to be equal ($p < 0.05$).

One unexpected comparison was observed between M.V.C. and C.M.C. mean torques for subjects stimulated by the Medelco current format. It was suggested that since the C.M.C. condition involved a M.V.C. component as well as an E.M.S. component, the mean torque generated under this contraction condition would be no less than that generated by M.V.C. alone. The results of Table 1 however, showed that mean torque generated under the C.M.C. condition for M.S. was lower (although not significantly) than respective M.V.C. mean torque. A postulative explanation for the comparative discrepancy again pertained to the degree of sensation perception associated with the Medelco current format. It was possible the increased current sensation associated with the Medelco unit distracted subjects and interfered with performance of the simultaneous maximum voluntary contraction.

The third null hypothesis stated that mean maximal torque recorded in any of the four (4) trials, irrespective of the type of contraction or E.M.S. unit used, was equal to the mean torques obtained from any of the respective remaining trials. Failure to reject this null hypothesis was based on the results of Table 1 and suggested that no learning effect altering subsequent performance within a particular contraction condition was present. A progressive rise or decrease in the mean torque developed during each of a subject's four (4) trials under each contraction condition, would have suggested that the subject gained pertinent knowledge from the initial trial(s) which altered subsequent performance(s), either negatively or positively.

Implications from the above finding were particulary important when a contraction condition necessitated the use of electrical muscle

stimulation. When E.M.S. was used, subject performance remained constant throughout the four (4) trials indicating that a discernible and reproducible tolerance point for E.M.S. was maintained. It was suggested therefore that practice sessions were sufficient both in number and duration to allow familiarization and accustomization to the E.M.S. current.

Aside from the scientific findings of this study, one further development arose with two (2) subjects which had not been documented in any previous E.M.S. studies. Both subjects developed symptoms of light headedness and pallor after experiencing E.M.S. for the first time. These symptoms would recede after a moments rest but were immediately reproducible every time the subject turned up the intensity dial until conscious perception of the electrical current was made. One subject was very apprehensive at the beginning of the study over the prospects of a machine contracting his muscle. This extreme apprehension could possibly explain the symptoms in this case. The second subject, however, reassured the author that he was not overly concerned by the procedure to be employed and even after the initial reaction, was adamant about continuing with the experiment, although without success. Both subjects were dropped from the study and two (2) replacement subjects used.

CONCLUSION

The conclusions drawn from this study were several. First, since mean torque generated under either the E.M.S. only or C.M.C. contraction condition never surpassed M.V.C. mean torque, it was concluded that E.M.S. did not recruit more motor units, resulting in a stronger force of contraction than maximal voluntary contraction. In fact, depending on the electrical stimulator and current format used, fewer motor units were often recruited. Second, it was found that the three E.M.S. current formats were associated with different maximal E.M.S. only torques, with the TECA format generating the highest followed by the Medelco and Siemens formats respectively. It was concluded within the limitations of the study that different current format composition and maximal administrable intensities available for each E.M.S. unit were jointly responsible for the maximal, E.M.S. only, mean torque discrepencies.

Based on the outcomes of this study, it was concluded that E.M.S. is potentially no more effective for the hyperdevelopment of normal muscle than the more traditional voluntary strength improvement techniques.

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APPENDIX 1

POST TEST QUESTIONNAIRE

QUESTIONNAIRE

1. Did you feel you were at as high an intensity level as could be tolerated?

TECA

Number of Responses	Type of Response
8	Yes
2	No

MEDELCO

Number of Responses	Type of Response
7	Yes
3	No

SIEMENS

Number of Reponses	Type of Response
1	Yes
9	No

QUESTIONNAIRE

2. When you reached your maximum intensity, what was the main factor limiting you from going higher?

TECA

Number of Responses	Type of Response
2	Maximum intensity machine could supply
3	Pain
1	Apprehension
3	Muscle was contracting as hard as it seemed possible
1	Fatigue

MEDELCO

Number of Responses	Type of Response
5	Maximum intensity machine could supply
4	Pain
1	Apprehension

SIEMENS

Number of Responses	Type of Response
10	Maximum intensity machine could supply

QUESTIONNAIRE

3. Based solely on the sensation within the muscle, did you feel electrical muscle simulation produced a stronger, equal or weaker contraction than maximum voluntary contraction?

TECA

Number of Responses	Type of Response
8	Stronger
0	Equal
2	Weaker

MEDELCO

Number of Responses	Type of Response
6	Stronger
1	Equal
3	Weaker

SIEMENS

Number of Responses	Type of Response
4	Stronger
0	Equal
6	Weaker

QUESTIONNAIRE

4. In your opinion, were you able to turn the intensity dial up higher (ie. tolerate more current) and produce a stronger contraction when the electrical muscle stimulation was used alone or when it was combined with simultaneous maximum voluntary effort?

TECA

Number of Responses	Type of Response
8	Combined
1	Alone
1	No Difference

MEDELCO

Number of Responses	Type of Response
8	Combined
1	Alone
1	No Difference

SIEMENS

Number of Responses	Type of Response
10	Combined
0	Alone
0	No Difference

APPENDIX 2

POST HOC COMPARISONS

WITHIN GROUPS

Scheffe Post Hoc Comparisons of the Three Contraction Condition Mean Torques Within Each of The Groups Stimulated By Different E.M.S. Current Formats

TECA

	M.V.C.	E.M.S.	C.M.C.
C.M.C.	0.451	1.154	--
E.M.S.	1.239	--	
M.V.C.	--		

MEDELCO

	M.V.C.	E.M.S.	C.M.C.
C.M.C.	1.383	2.303*	--
E.M.S.	2.686*	--	
M.V.C.	--		

*significant at the $p < 0.05$ level

SIEMENS

	M.V.C.	E.M.S.	C.M.C.
C.M.C.	0.604	3.311*	--
E.M.S.	3.256*	--	
M.V.C.	--		

*significant at the $p < 0.05$ level

APPENDIX 3

POST HOC COMPARISONS

BETWEEN GROUPS

Scheffe Post Hoc Comparisons of the Three Contraction Condition Mean Torques Between Each of The Groups Stimulated By Different E.M.S. Current Formats

M.V.C.

	TECA	MED	SIEM
SIEM	0.933	0.711	--
MED	0.604	--	
TECA	--		

E.M.S.

	TECA	MED	SIEM
SIEM	2.863*	1.696*	--
MED	2.306*	--	
TECA	--		

*significant at the $p < 0.05$ level

C.M.C.

	TECA	MED	SIEM
SIEM	1.200	1.668	--
MED	1.159	--	
TECA	--		

APPENDIX 4

TEST PROCEDURE RELIABILITY

MEASURE

Correlation Matrix Product Moment Correlation For Testing Procedure Reliability Measure

Subject	MVC Test	MVC Retest
C.W.	24.9	22.3
D.B.	25.5	28.7
J.H.	24.1	25.3
R.S.	25.0	29.3
G.M.	25.9	27.7
H.G.	32.5	30.7
D.B.	26.3	24.9
C.L.	33.1	37.1
K.K.	32.3	30.5
P.H.	21.3	21.3
G.F.	26.1	27.3
P.L.	17.8	16.7
N.C.	26.6	25.0
J.G.	15.3	15.6
I.L.	26.4	26.6

N= 15 DF= 13 R@ .0500= .5140 R@ .0100= .6411

CORRELATION BETWEEN TEST AND RETEST = .9165

APPENDIX 5

TEST INSTRUMENT RELIABILITY

AND VALIDITY MEASURES

Reliability and Validity Measures of the Test Instrument

Actual (kgm)	Calculated (Trials 1 - 5) 1 (kgm)	2 (kgm)	3 (kgm)	4 (kgm)	5 (kgm)	Standard Error of the mean
9.9	9.7	9.7	9.7	9.8	9.7	0.02
19.9	19.8	19.7	19.8	19.7	19.7	0.02
29.9	29.9	29.7	29.7	29.7	29.7	0.02
40.1	39.4	40.0	40.0	40.0	40.0	0.11

APPENDIX 6

INFORMED CONSENT

The University of Alberta

Department of Physical Education

INFORMED CONSENT FORM FOR INVESTIGATIVE STUDY:

COMPARISON OF ELECTRICAL STIMULATION AND

MAXIMUM VOLUNTARY CONTRACTION ISOMETRIC TORQUES.

Outline of Procedures (retained by subject)

In recent years the use of high intensity electrical stimulation as a means of improving muscular strength has received considerable publicity. The "Russian Technique" of electrical stimulation claims to produce 30 to 40 percent strength gains over 4 to 5 weeks of training, in already highly trained athletes.

The basis for this claim is that electrically induced muscular contractions can activate all the muscle fibers in a muscle while voluntary contraction, even at maximal effort, can activate only 60 to 70 percent of the muscles' fibers. If this is the case, then the 30 percent greater electrical stimulation induced contraction forces reported by the Soviets are not unrealistic. Furthermore, the 30 to 40 percent strength improvements with electrical stimulation training may be possible.

Unfortunately, the available information describing the work carried out by the Soviets is incomplete thus limiting the credibility of the Russian claims. In addition, Western researchers have not extensively examined this mode of training. It is not know how effective or ineffective electrical stimulation training really is.

The first step in examining this mode of strength training is to compare the force produced by a maximal voluntary contraction with that produced during an electrically induced contraction of the same muscle. In this study a number of different types of electrical muscle stimulators are to be used. The results derived from this study will not only help validate the Soviet claims but will also provide insight into which particular current format best meets the requirements for maximal contractile performance.

The study in which you are being requested to participate will compare maximum voluntary knee extension (or straightening) force with the force produced during an electrically induced knee extension. You will be seated, your trunk and thighs secured to the testing chair and you will attempt to extend your knee against a padded resistance arm (positioned just above your ankle). All muscular efforts will be of an isometric (no movement) nature.

You will be required to participate in two practice sessions prior to the actual testing session. Two full days off are provided between each of the stimulation sessions. When electrically stimulated muscle contractions are to be performed, one large electrode will be placed on your lower back while a smaller electrode, which is responsible for initiating the contraction, will be positioned high up on the front of your thigh. The intensity of the current will gradually be increased by you until you feel you are accepting a maximally tolerated stimulus intensity. It is important to note that you will determine the acceptable level of electrical stimulation, no dosage is assigned, and you or the investigator can terminate the stimulus at any time if so desired.

The electrical stimulus will at first give a prickling sensation on the skin. As the stimulation intensity increases, you will begin to feel the quadricep muscles contract with greater and greater force. At the maximally tolerated current intensity, you will feel a combination of skin prickling sensation plus a very strong muscular contraction. The muscular contraction sensation will be similar to that which you have experienced in traditional resisted exercise.

The intensity of the electrical stimulus to be utilized is far below that obtained from normal household current. The equipment has been inspected by the Canadian Standards Association, and the investigators are familiar with electrical stimulation techniques, having developed the study protocol on themselves. You will be notified as to when the stimulus is to commence or end. The danger of electrical shock and/or burn is minimal and is comparable to that existing in routine physiotherapy procedures.

As a result of the high muscular contraction forces involved, there exists a possibility of muscular discomfort occurring after the exercise sessions. However this should be absent or minimal, in most cases, and, if experienced, should be similar to that experienced during and after routine hard workouts. The possibility of 'pulling' or straining a muscle is considered to be minimal and has not been reported in the literature to date.

The total time for testing will be approximately 20 to 30 minutes for each of the practice and the test sessions. It is hoped that you will be able to participate in all of the required sessions.

In the event of questions please feel free to contact Mr. David Lindsay (432-5503) or Dr. John Kramer (432-2071). You have the right to withdraw from participation at any time. No records or photographs which would permit your identification will be made public or used in any medical article without your written permission to do so.

The University of Alberta

Department of Physical Education

INFORMED CONSENT FORM FOR INVESTIGATIVE STUDY:

COMPARISON OF ELECTRICAL STIMULATION AND

MAXIMAL VOLUNTARY CONTRACTION ISOMETRIC TORQUES

Subject Consent (retained by investigators)

I ____ do hereby agree to participate as a subject in the study entitled "Comparison of Electrical Stimulation and Maximal Voluntary Contraction Isometric Torques" conducted by Mr. David Lindsay. The nature of this study has been explained to me and I understand the potential risks involved. I do not suffer at present, nor have I ever suffered, any serious knee or hip injury which could interfere with or be affected by participation in this study. I have been advised that I may withdraw from the study at any time.

______________________________	______________________________
Subject's Signature	Date
______________________________	______________________________
Address	Phone Number

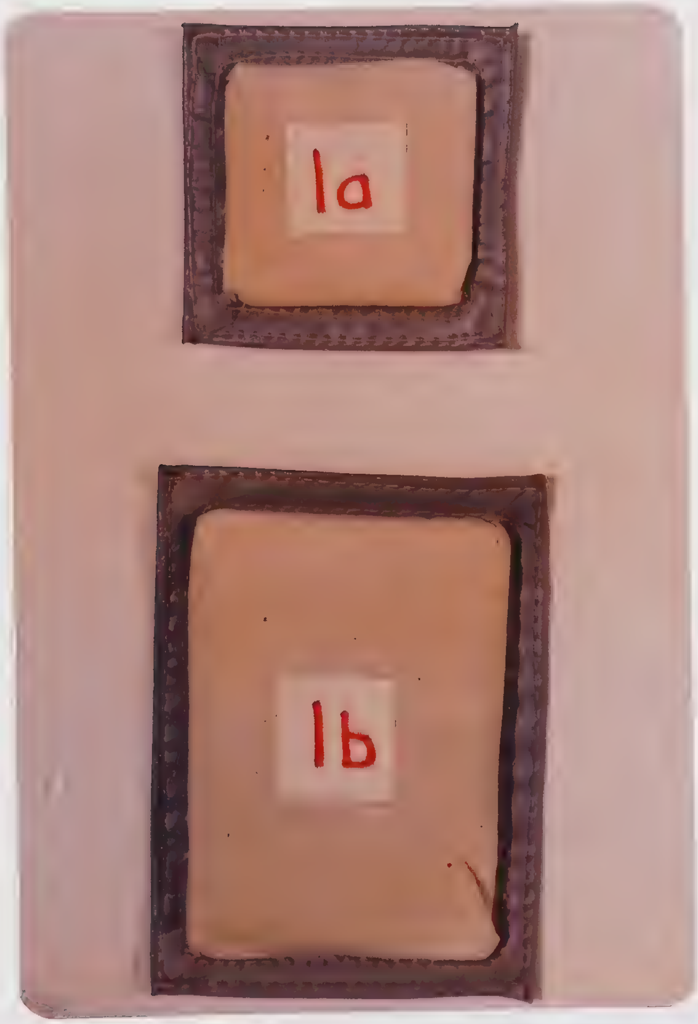
I was a witness during the above explanation and to the signature.

______________________________	______________________________
Witness' Signature	Date

APPENDIX 7

EMS ELECTRODE

PADS AND PLATES



TECA electrode plates and pads

Medelco and Siemens electrode plates and pads